

The Muon Magnetic Moment Anomaly: Experiment

James Miller

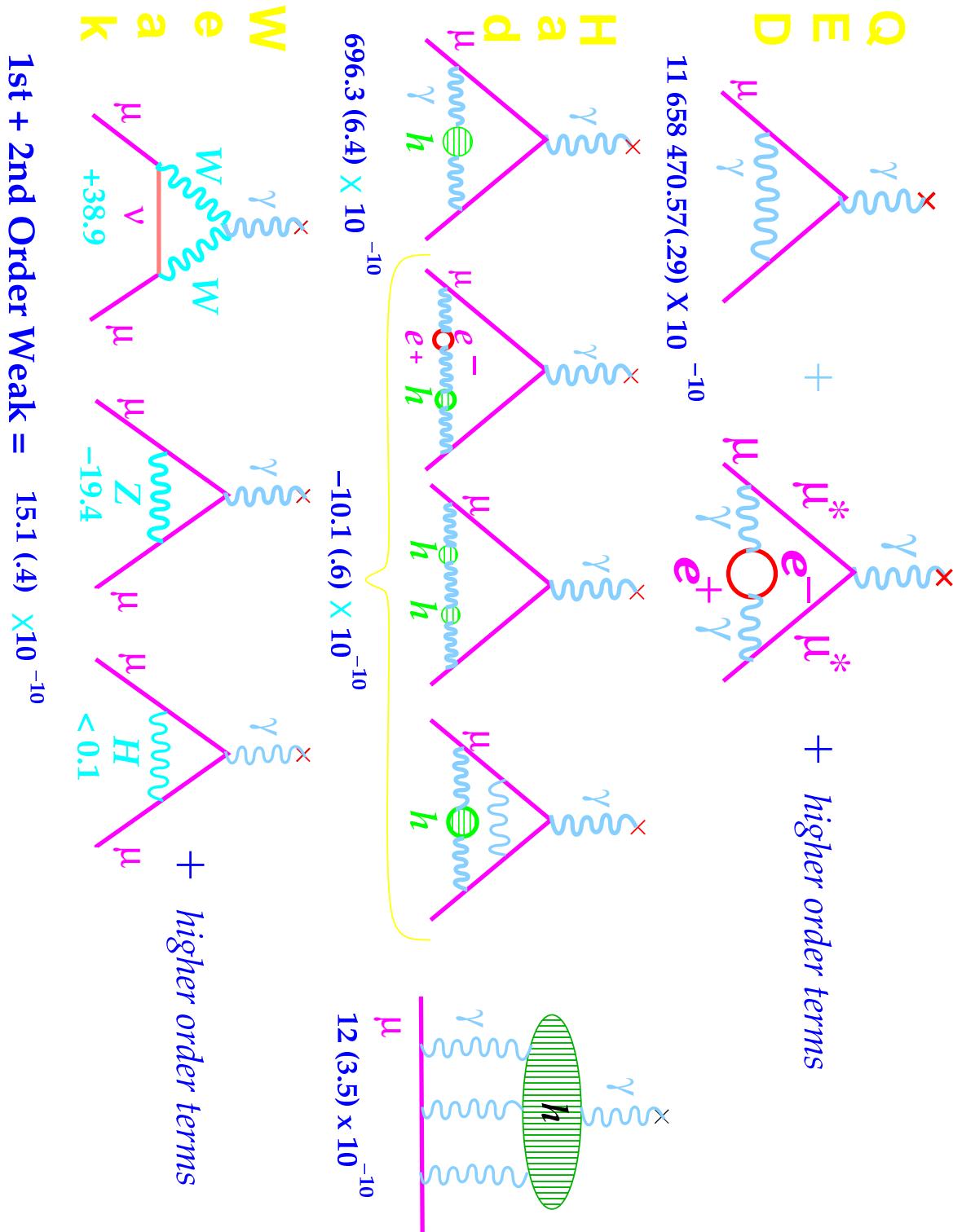
Boston University

From 0 to Z^0 FNAL 12-14 May 2004

Outline

- Introduction
- Theory Status- brief
- Data/Theory Comparison: Case for a Future Run
- Experimental Method
- Conclusions and Future Prospects

Theory for Muon ($g - 2$)

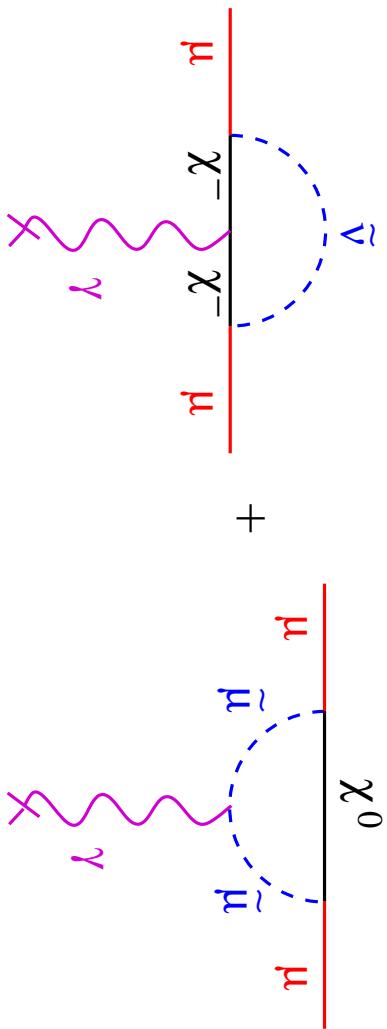


$$1\text{st} + 2\text{nd Order Weak} = 15.1(4) \times 10^{-10}$$

Search for “NEW” Physics

$$\Delta a_\mu^{NEW} = a_\mu^{exp} - a_\mu^{theory}$$

- Supersymmetry



$$\Delta a_\mu^{SUSY} \approx 140 \times 10^{-11} \cdot \left(\frac{100\text{GeV}}{\tilde{m}}\right)^2 \tan(\beta)$$

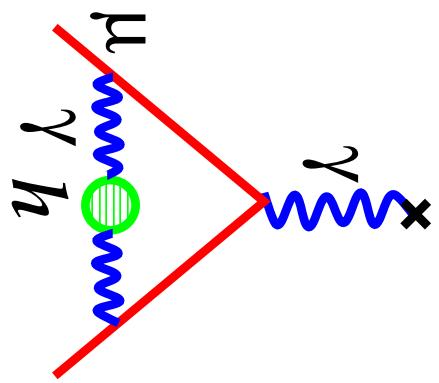
- Muon Substructure:

$$\Delta a_\mu^\lambda \approx \left(\frac{m_\mu}{\Lambda}\right)^2$$

- Sensitivity to New Particles:

$$\Delta a_\mu^\Lambda \approx \left(\frac{m_\mu}{m_{np}}\right)^2$$

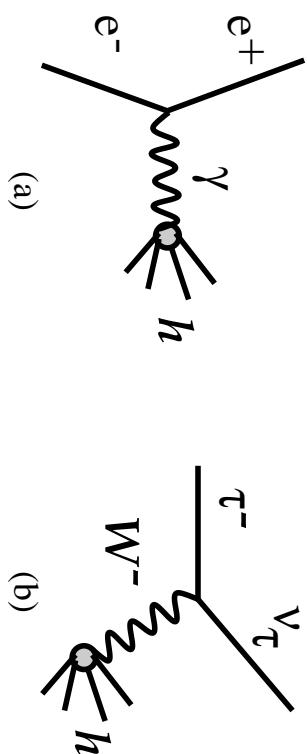
$a_\mu(HAD; 1) =$ Lowest order
hadronic contributions



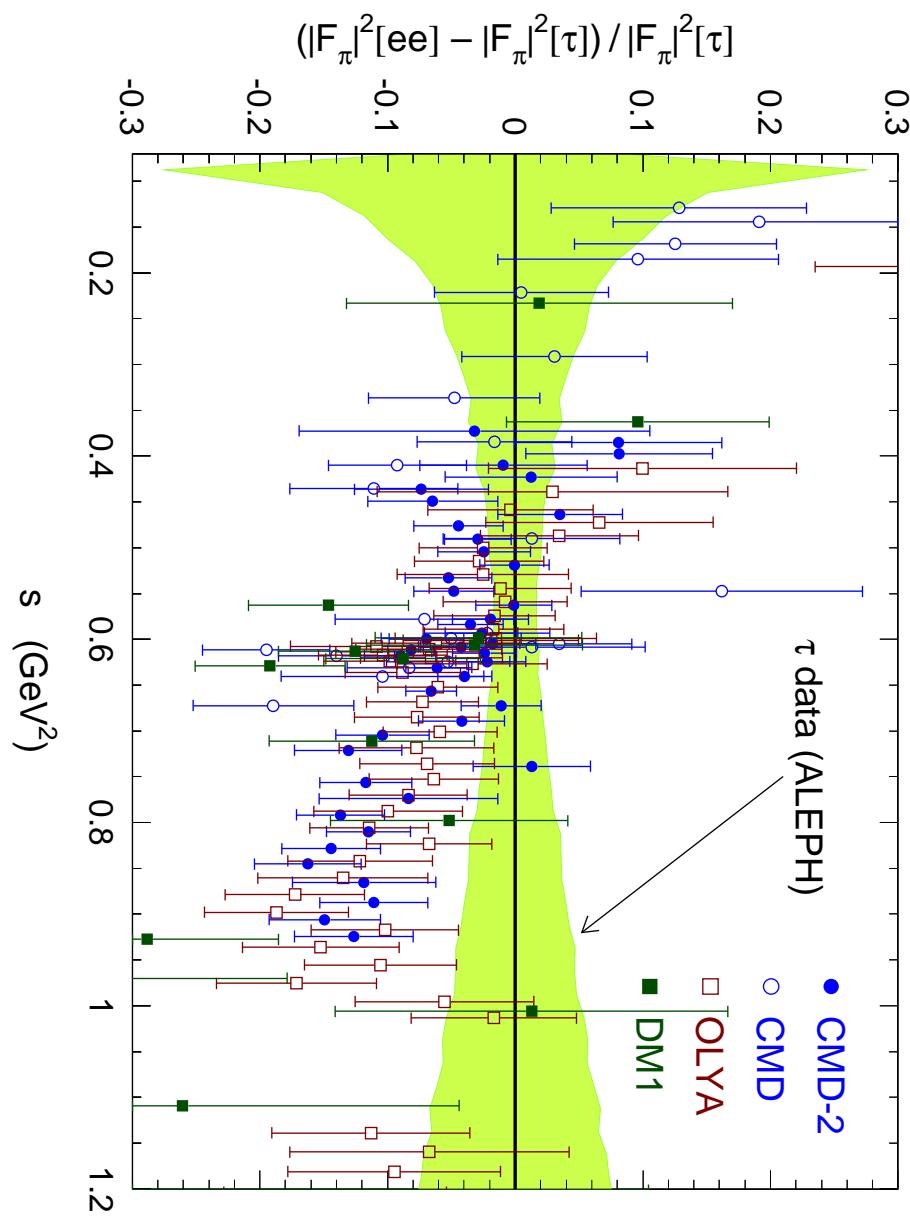
Determined from experimental data (low q loops) and/or
QCD (high q loops), using $R(s) = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ and:

$$a_\mu(had; 1) = (\frac{\alpha m_\mu}{3\pi})^2 \int_{4m_\pi^2}^\infty \frac{ds}{s^2} K(s) R(s)$$

$$\begin{aligned} a_\mu(ee) &= 694.4(7.2) \times 10^{-10} \\ a_\mu(\tau) &= 711.0(5.8) \times 10^{-10} \\ \Delta &= 16.6(9.2) \times 10^{-10} \text{ (1.8 s.d.)} \\ \Delta B(\tau^- \rightarrow \nu_\tau \pi^- \pi^0) & (2.9 \text{ s.d.}) \end{aligned}$$



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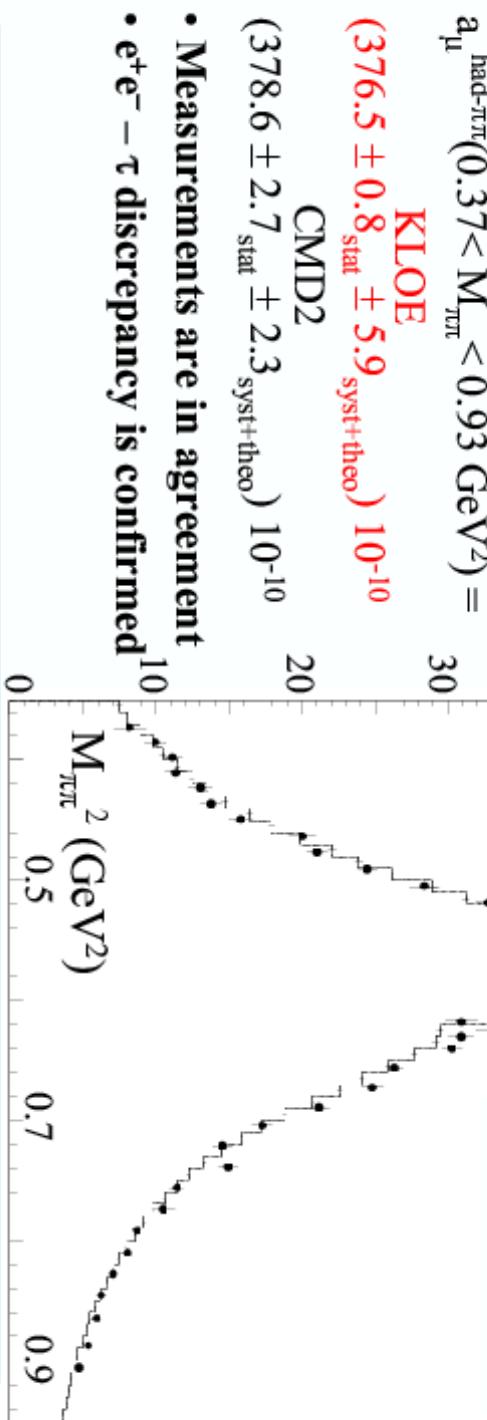
$a_\mu - \text{Preliminary results}$



Calculating the dispersion integral, $\sigma(e^+e^- \rightarrow \pi^+\pi^-) = \frac{\pi \alpha^2}{3M_{\pi\pi}^2} \beta^3 |F_\pi(M_{\pi\pi})|^2$

$a_\mu^{\text{had-}\pi\pi}(0.35 < M_{\pi\pi} < 0.95 \text{ GeV}^2) =$	$(389.2 \pm 0.8_{\text{stat}} \pm 4.7_{\text{syst}} \pm 3.9_{\text{theo}}) 10^{-10}$
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- Comparison with CMD2:
- KLOE
- CMD2

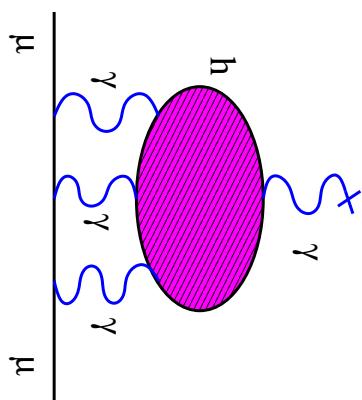


Recent results from KLOE at DAΦNE – T. Spadaro – La Thuile, 5 March 2004

(provided by Juliet Lee-Franzini)

Hadronic Light-on-light

Sign change
Old: $-8.5(2.5) \times 10^{-10}$
New: $+8.6(3.0) \times 10^{-10}$



Avg of: Hayakawa, Kinoshita PRD57(1998)465; Bijnens, Pallante, Prades, NP B474(1996)379.

Sign correction from: Knecht, Nyffeler, PRD65, 073034(2002).

Confirmed: Hayakawa, Kinoshita, hep-ph/0112102; Bijnens, Pallante, Prades, NP B626, 410(2002).

New Evaluation: Melnikov, Vainshtein, hep-ph/0312226

Match short- and long-range behavior: $13.6(2.5) \times 10^{-10}$

Adapted by Davier and Marciano: $12.0(4.0) \times 10^{-10}$

BNL E821-A New Precision Measurement of Muon ($g - 2$)

Boston University

Brookhaven National Laboratory

Budker Institute - Novosibirsk

Cornell University

Groningen

University of Heidelberg

University of Illinois

Max Planck Institute für Med. Forschung - Heidelberg

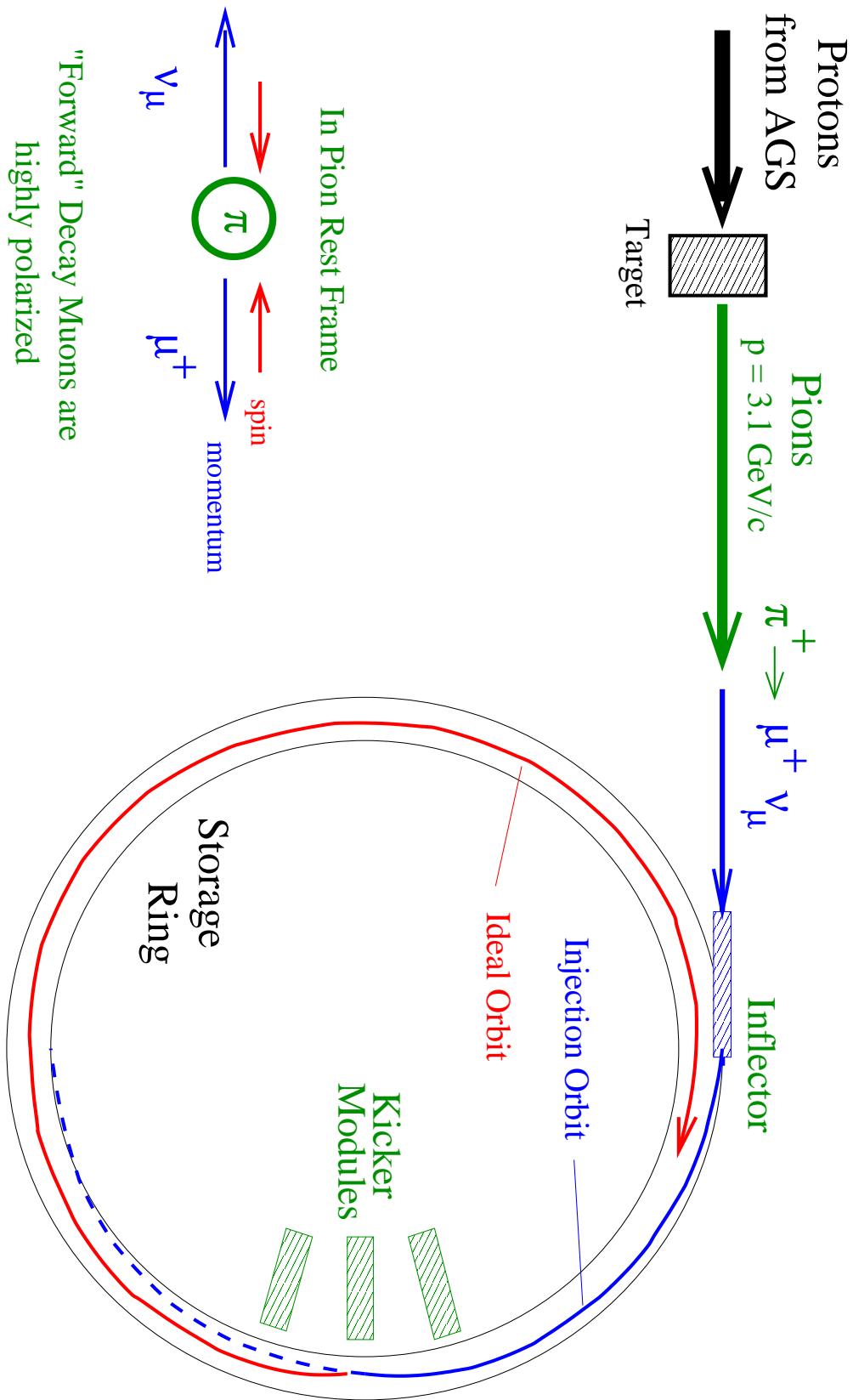
University of Minnesota

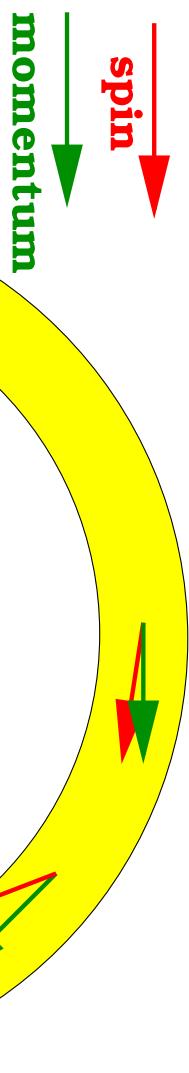
Tokyo Institute of Technology

KEK

Yale University

$(g-2)_\mu$ Experiment at BNL





$$\omega_a = \frac{a_\mu eB}{mc}$$

Storage
Ring

(exaggerated ~20x)

With homogeneous \vec{B} , all muons precess at same rate

Homogeneity \rightarrow need less detailed knowledge of orbits

Use Quadrupole electric field for focusing

With homogeneous \vec{B} , use quadrupole \vec{E} to focus and store beam

Spin Precession with \vec{B} and \vec{E}

$$\vec{\omega}_a = -\frac{e}{mc} [a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1}) \vec{\beta} \times \vec{E}]$$

"Magic" $\gamma = \sqrt{\frac{1+a}{a}} \cong 29.3 \rightarrow$ Minimizes the $\vec{\beta} \times \vec{E}$ term

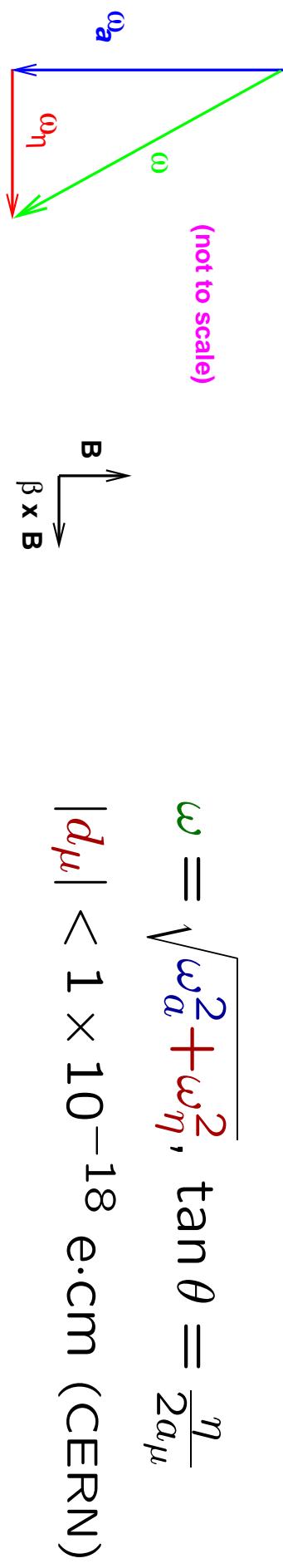
- $\gamma \cong 29.3 \rightarrow p_\mu \cong 3.09 \text{ GeV/c}$
- $B \cong 1.45T \rightarrow$ Storage ring radius $\cong 7.112m$
- $T_c \cong 149.2ns \quad T_a \cong 4.365\mu s$
- $\gamma\tau \cong 64.4\mu s$

(Range of stored momenta: $\cong \pm 0.3\%$)

Spin Precession with \vec{B} and \vec{E} and an EDM

$$\vec{\omega} = \frac{e}{mc} [a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1}) \vec{\beta} \times \vec{E} + \frac{\eta}{2} (\vec{\beta} \times \vec{B} + \vec{E})]$$

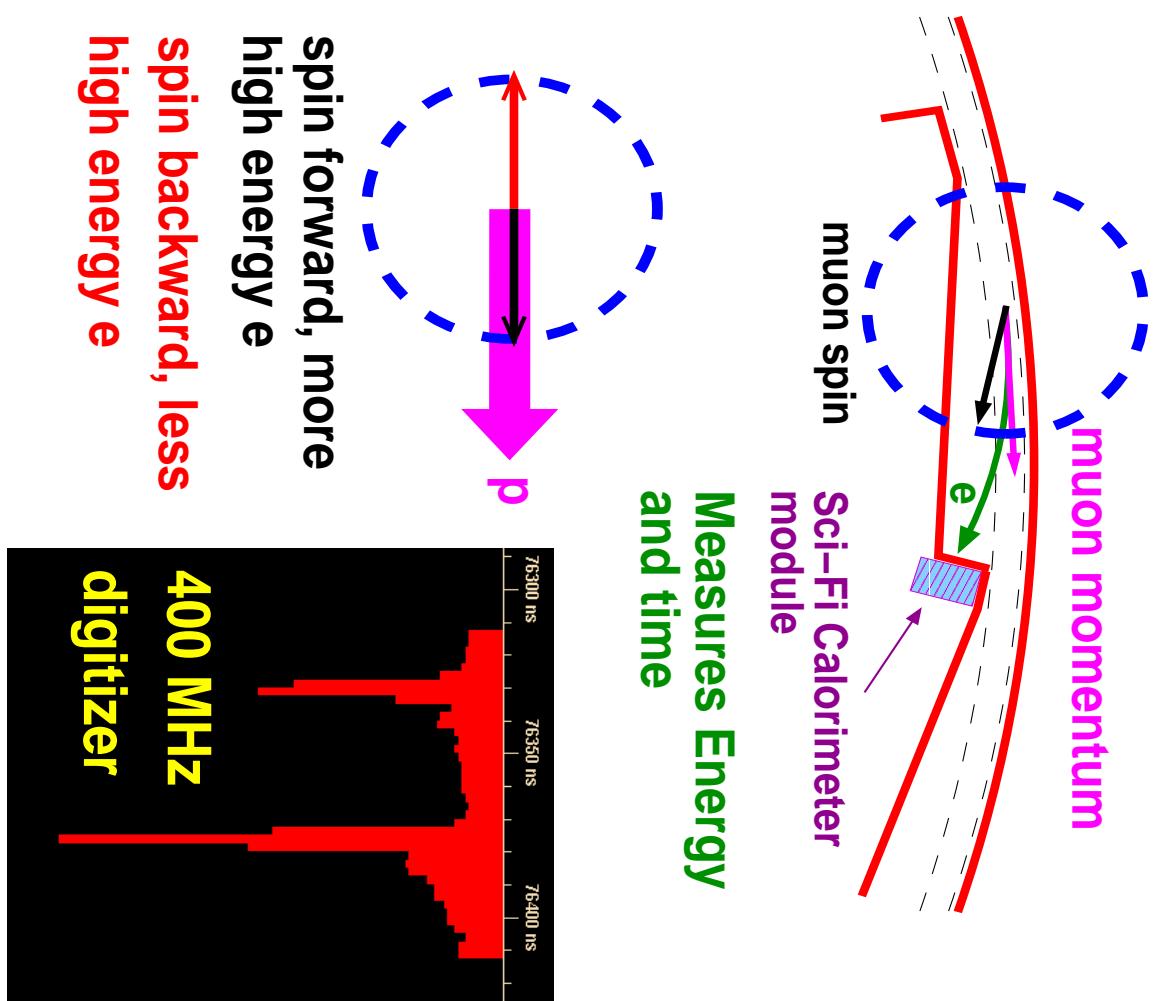
where **EDM** = $d_\mu = \frac{\eta}{2} (\frac{e\hbar}{2mc})$



Better idea: Choose $\vec{B} = B_0 \hat{z}$, $\vec{E} = E_0 \hat{r}$, γ so that

$$\omega_a = a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1}) \vec{\beta} \times \vec{E} = 0 \rightarrow \rightarrow$$

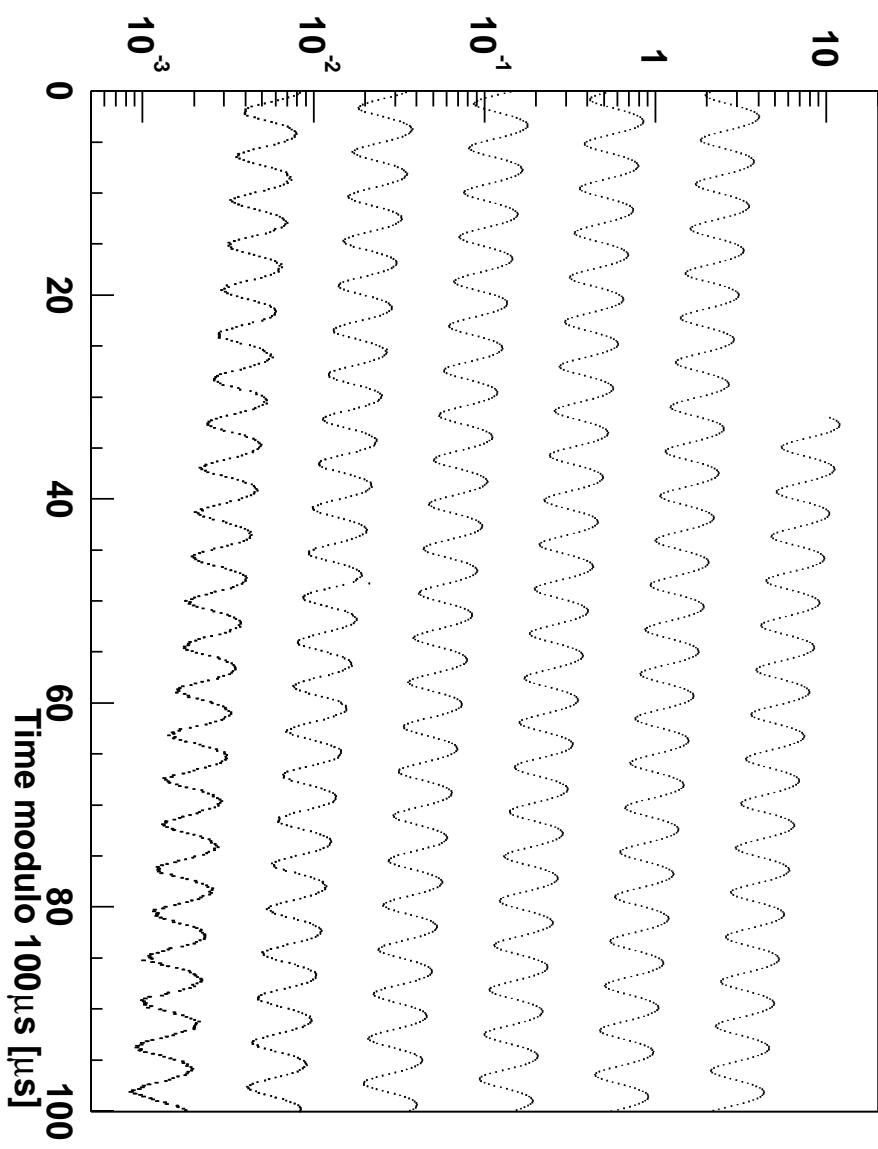
$$\omega = \omega_d = \frac{\eta}{2} (\vec{\beta} \times \vec{B} + \vec{E}) = constant \times \eta \times \hat{r}$$



Log plot of 2001
data, $E > 2$ GeV
100 μ s segments

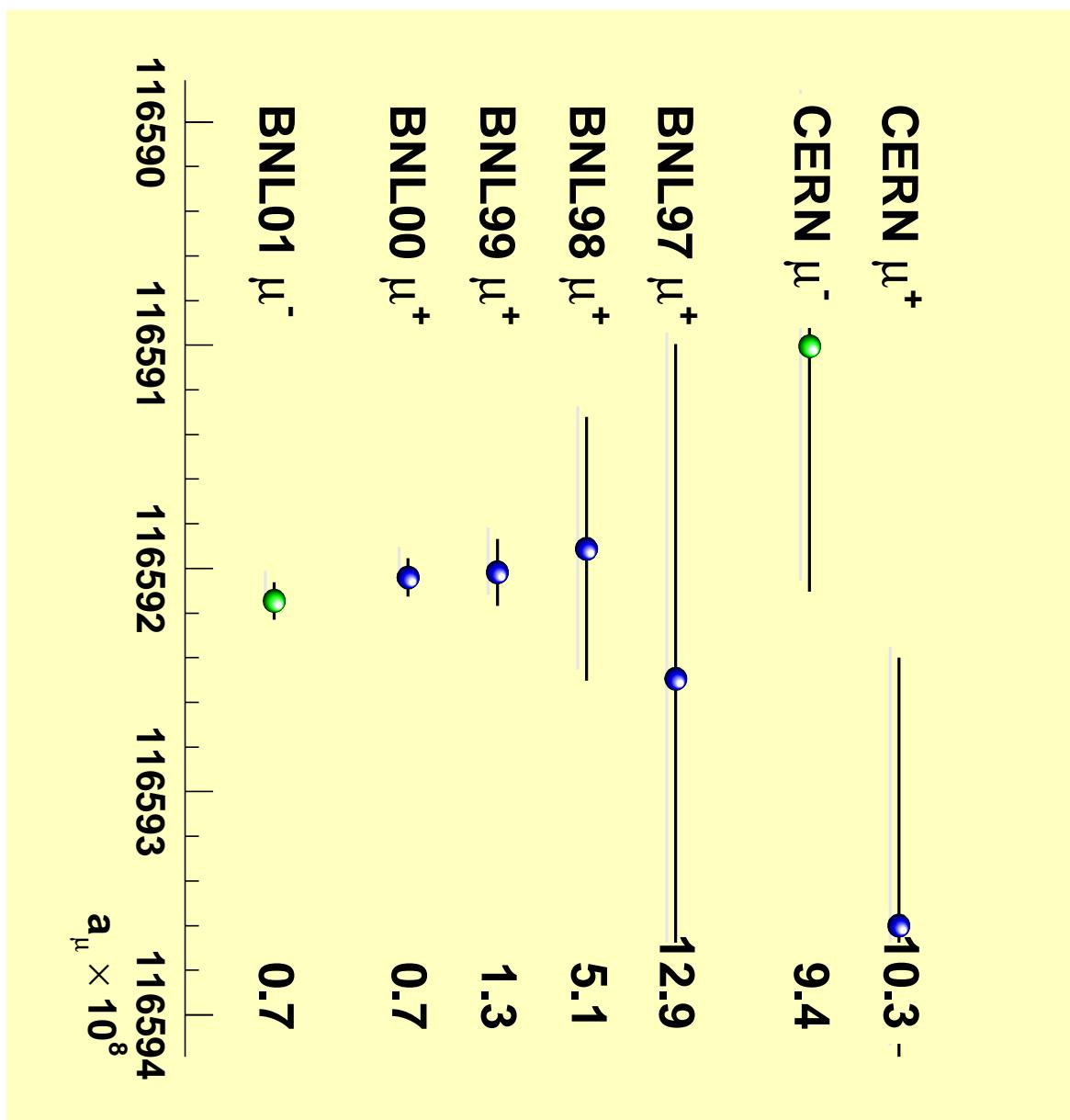
Statistical error:

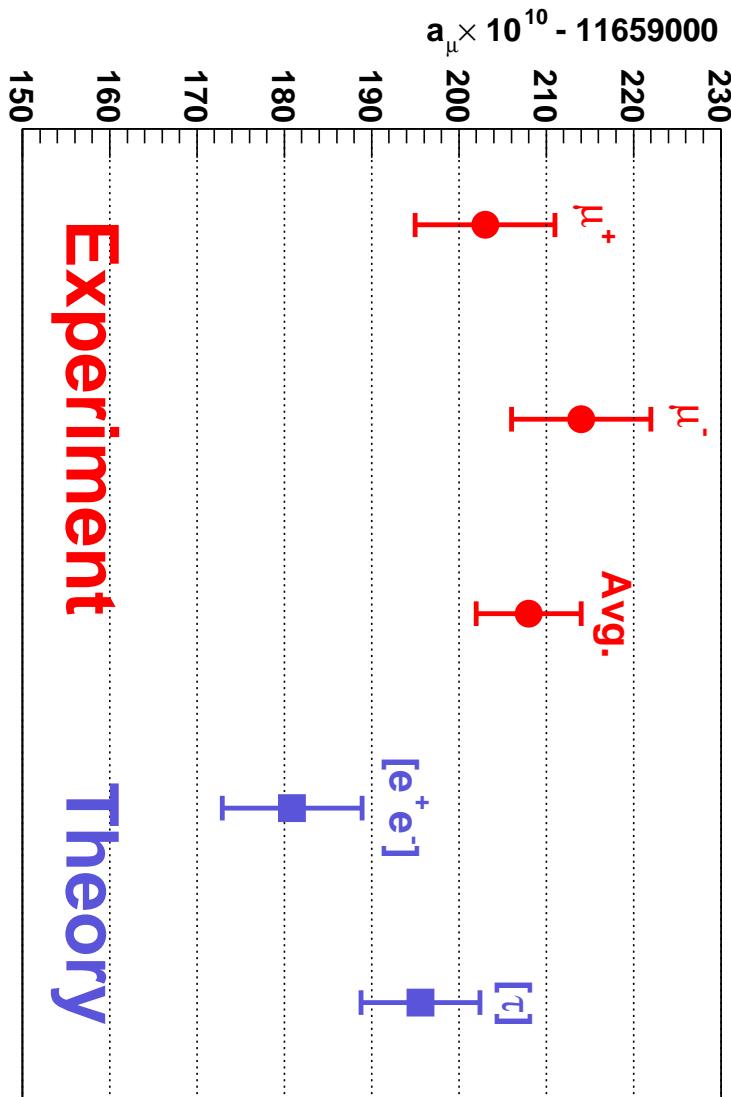
≈ 0.6 ppm



5-parameter function (OK to fit 1998 data set)

$$N(t) = N_0 e^{-\lambda t} [1 + A \sin(\omega_a t + \phi)]$$





Experiment Theory

$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.4 \text{ s.d.}$$

$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}$$

Plans for a Future Data Run

Current: $\frac{\delta a_\mu}{a_\mu} = 0.5 \text{ ppm}$

- Systematic uncertainty(2001): 0.27 ppm
(0.17 ppm B-field, 0.21 ppm precession frequency)
- Statistical uncertainty: 0.42 ppm

Goal: $\frac{\delta a_\mu}{a_\mu} = 0.25 \text{ ppm}$

- Systematic uncertainty: 0.14 ppm
- Statistical uncertainty: 0.21 ppm

To get factor of two reduction in overall uncertainty:

- reduce systematic error by x2
- increase statistical sample by x3-4

Bottom line:

Capital eq. $\approx \$2$ million, running cost $\approx \$8$ million (25 weeks of AGS), proposal to BNL PAC July 2004.

Statistics Increase Needed for a Future Run

- $\times 6$ More Muons than μ^- run

With $\times 3$ rate increase, need 25 weeks AGS

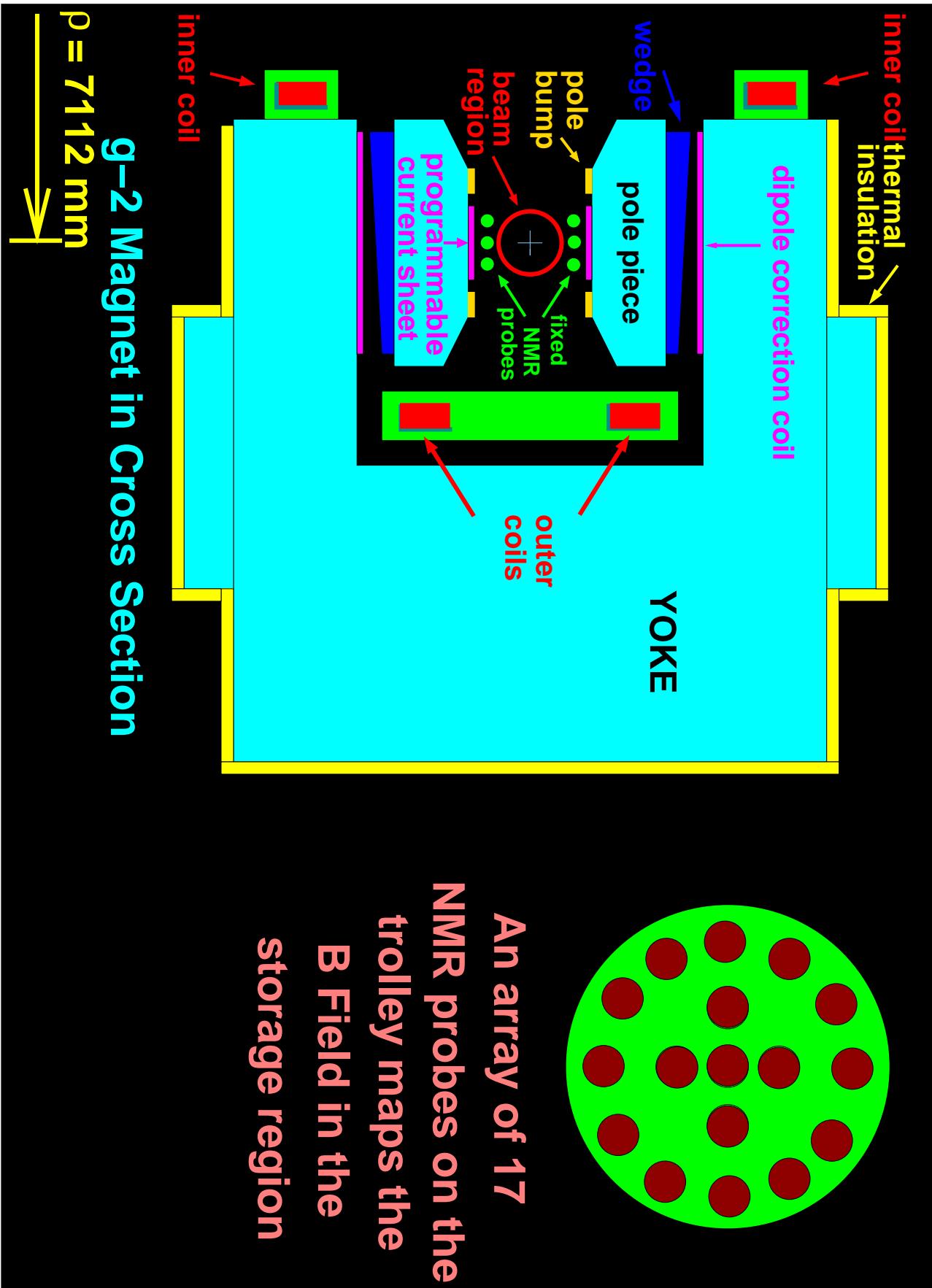
Relatively straightforward improvements:

- Open inflector ends to reduce multiple scattering, $\times 1.75$
- Use positive muons, $\times 1.2$
- More magnetic quadrupoles in beam line, $\times 2$

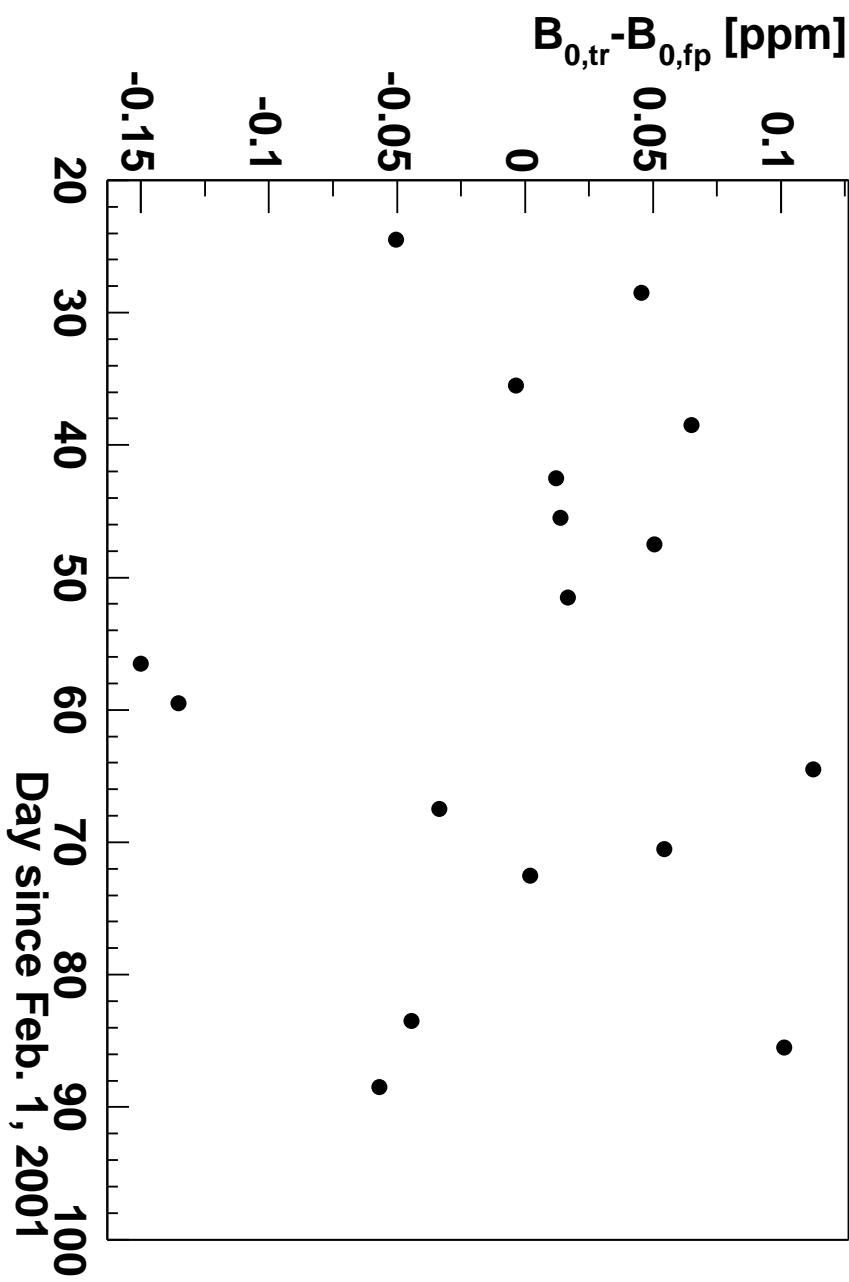
Total $\times 4$

More costly options (time or money)

- Redesign inflector with larger aperture, $\times 1.5$
- Backward muons, more magnetic quadrupoles, $\times 2$, no *flash*
- Target optimization/Li lens or horn, $\times 2$?

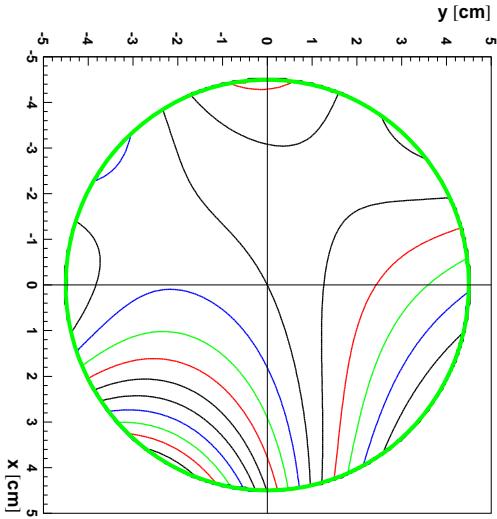


Difference between Trolley Maps and Fixed Probes

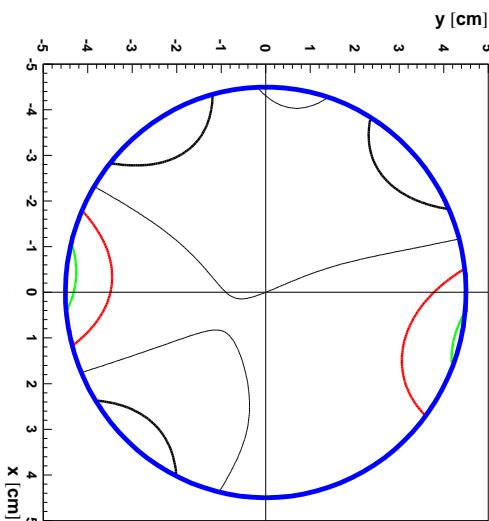


Magnetic Field Uniformity

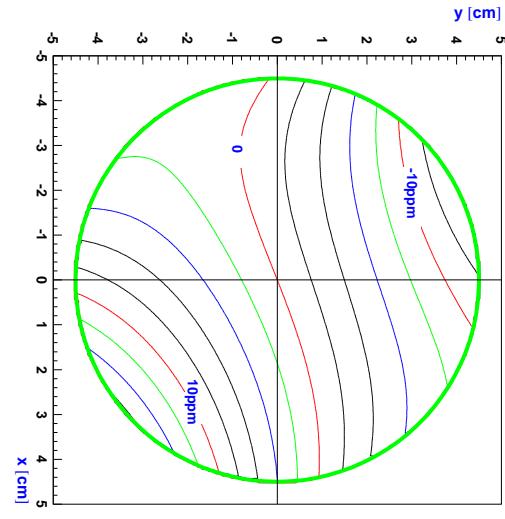
(Azimuthal Average, 1 ppm contours, except '97)



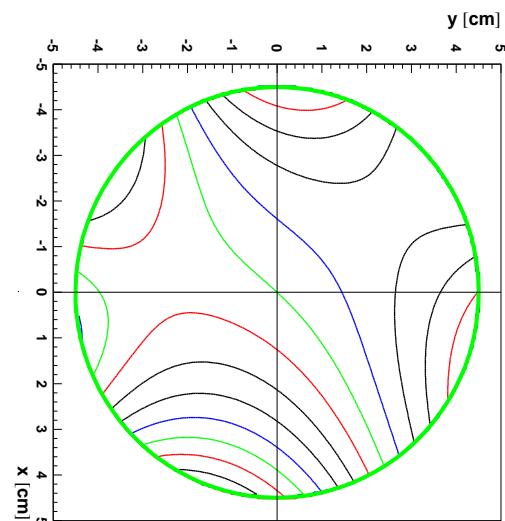
1999 run



2000 run



1997 run



1998 run

Systematic Errors on $\langle \omega_p \rangle$

Source	(ppm)	1999	2000	2001
Stand. Probe Absolute Calib.	0.05	0.05	0.05	
Calibration of trolley probes	0.20	0.15	0.09	
Trolley measurements of B_0	0.10	0.10	0.05	
Interpolation with fixed probes	0.15	0.10	0.07	
Uncertainty from μ -distribution	0.12	0.03	0.03	
Others [†]				
Inflector Fringe Field				
Total systematic error on ω_p	0.4	0.24	0.17	

[†] Higher multipoles, trolley temperature and voltage response, kicker eddy currents, time-varying stray fields.

2000 improvements: New Inflector with 5x less fringe field, Better trolley calibration

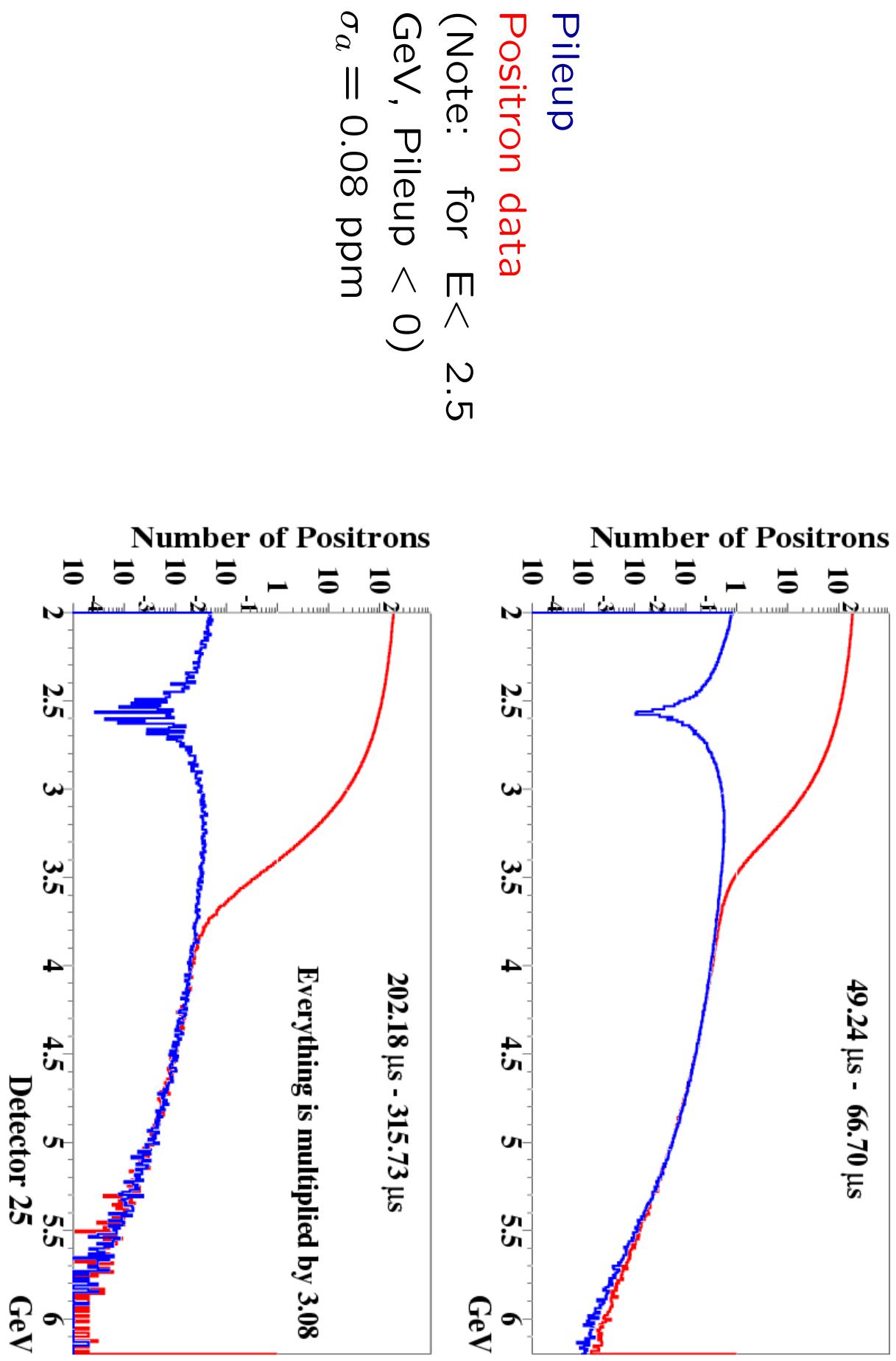
2001 improvements: refined calibrations, improved trolley position

1999-2001 Systematic Errors on $\langle \omega_a \rangle$

Source	(ppm)	1999	2000	2001
Pile-Up	0.13	0.13	0.08	
AGS Background	0.10	0.01	0.01	
Lost Muons	0.10	0.10	0.09	
Timing Shifts	0.10	0.02	0.02	
E-field and vertical β -motion	0.08	0.03	0.06	
Fitting Method / Binning	0.07	0.06	0.06	
Coherent Betatron Oscillation	0.05	0.21	0.07	
Beam debunching	0.04	0.04	0.04	
Detector Gain Changes	0.02	0.13	0.12	
Total systematic error on ω_a	0.3	0.31	0.21	

New in 2000

Sweeper magnet to eliminate AGS background



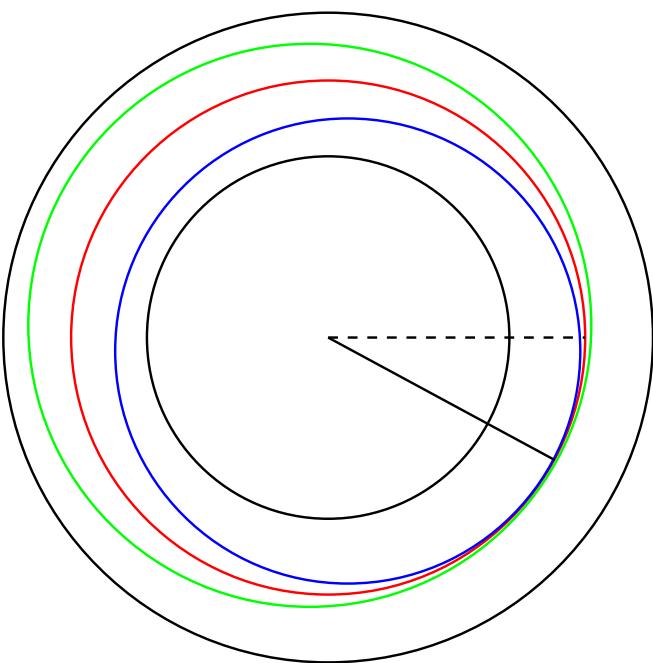
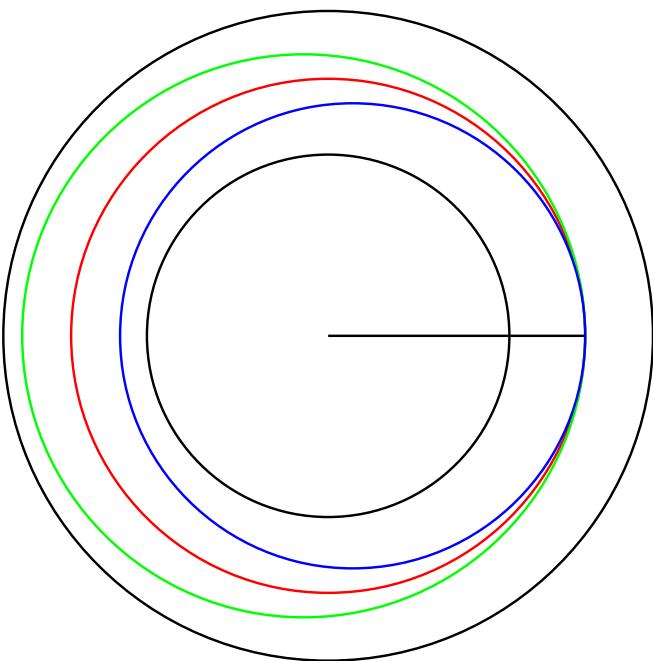
Improve Control of Pileup

- Increase segmentation in detector/PMT/WFD
 - Currently 4 elements in each detector are *summed* before digitization.
 - Better control of gains and pulse shapes of individual detector elements (crucial to the modeling process)

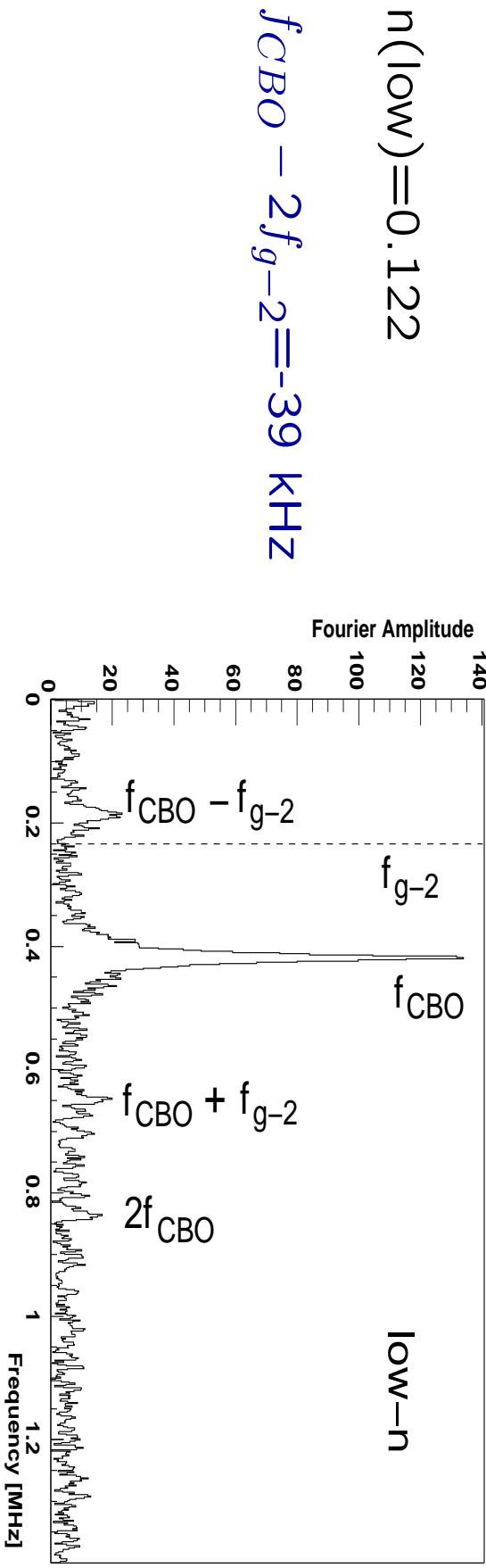
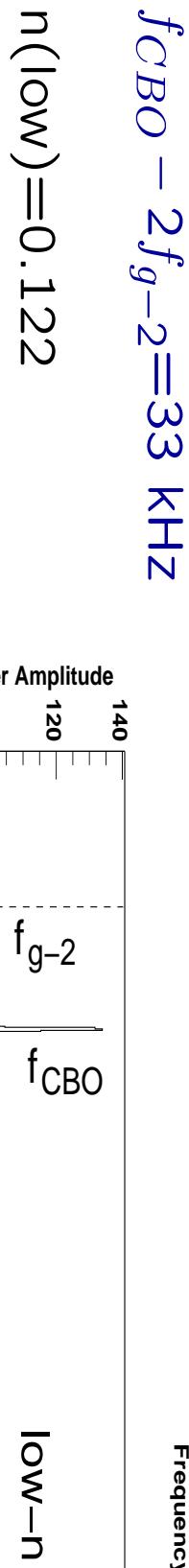
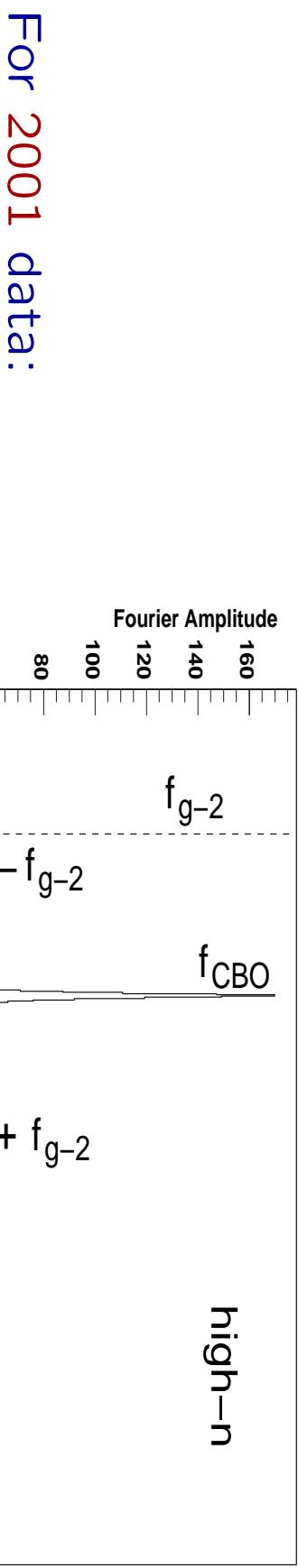
CBO- Coherent BetatronOscillations

Weak focusing index: $n = \frac{R_0}{cB_0} \frac{\partial E_y}{\partial y}$

Horizontal betatron oscillation in a ring, $f_h = f_c \sqrt{1 - n}$



In 2000 data set, $n \approx .137$, $f_{CBO} = f_c - f_h = 466$ kHz
-close to $2 \times f_a \approx 458$ kHz.



Effect of CBO on Fit to Muon Decay Spectrum

→ Oscillating beam position/width → Oscillating:

- detector acceptance
- distance traveled by electron from decay to detection
- shape of electron energy distribution

This leads to a Modified Distribution: $N =$

$$N_0 e^{-\frac{t}{\tau}} (1 + \textcolor{red}{A} \sin(\omega_a t + \phi)) (1 + A_{cbo} e^{-\frac{t}{\tau_{cbo}}} \sin(\omega_{cbo} t + \phi_{cbo}))$$

- modulation of N , $\textcolor{red}{A}_{cbo} \approx 0.01$, $f_{cbo} = f_c(1 - \sqrt{1 - n})$
- $A \rightarrow A \times (1 + A_1 e^{-(t/\tau_{cbo})} \sin(\omega_{cbo} t + \phi_1))$, $A_1 \approx .001$
- $\phi \rightarrow \phi \times (1 + A_2 e^{-(t/\tau_{cbo})} \sin(\omega_{cbo} t + \phi_2))$, $A_2 \approx 1$ mrad.
- $\tau_{cbo} \approx 100\mu s$
- A_1 and $A_2 \rightarrow$ artificial shifts in ω_a up to 4 ppm (individual detectors, 2000 data) when not accounted for.
Shifts largely cancel (factor ≈ 9) in sum of detectors due to circular symmetry.

Future run: Plans to reduce $\sigma_{\omega_a}(CBO)$

Currently: $\sigma_a(CBO) = 0.07$ ppm

- Choose n: CBO resonance frequencies far from f_a
- Improve orbit kick to reduce CBO amplitude
- Active RF to reduce CBO amplitude.
- Sextupole E or B field to damp out CBO
- Increase the size of inflector aperture

Muon Losses

- Minimized by 'scraping' beam at early times, $\approx 0 - 10\mu s$
- Lost muons monitored by scintillator elements at 11 detector stations.

- Losses $\approx 1\%$ per τ_μ at $50 \mu s$, 0.1% late times
- Distortion of $N(t)$ has minimal effect on value of ω_a
- Possibility: lose more muons with phase which differs from average

Contribution to $\sigma_{\omega_a} = 0.10 \text{ ppm}$

Ways to Reduce Error

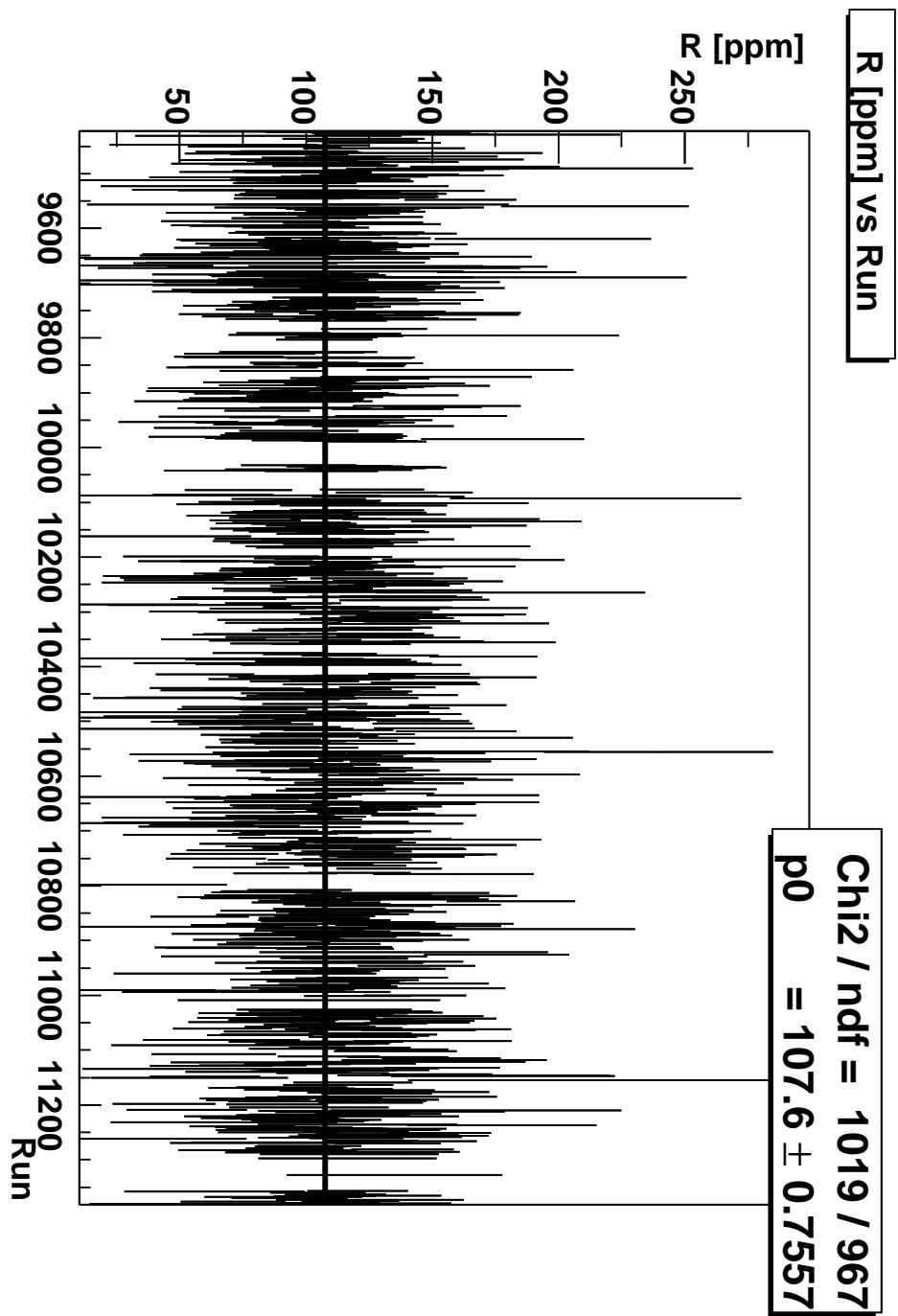
- Increase ring coverage of muon loss monitors
- Increase instrumentation of muon loss monitors
- Reduce muon loss rate- new scraping techniques

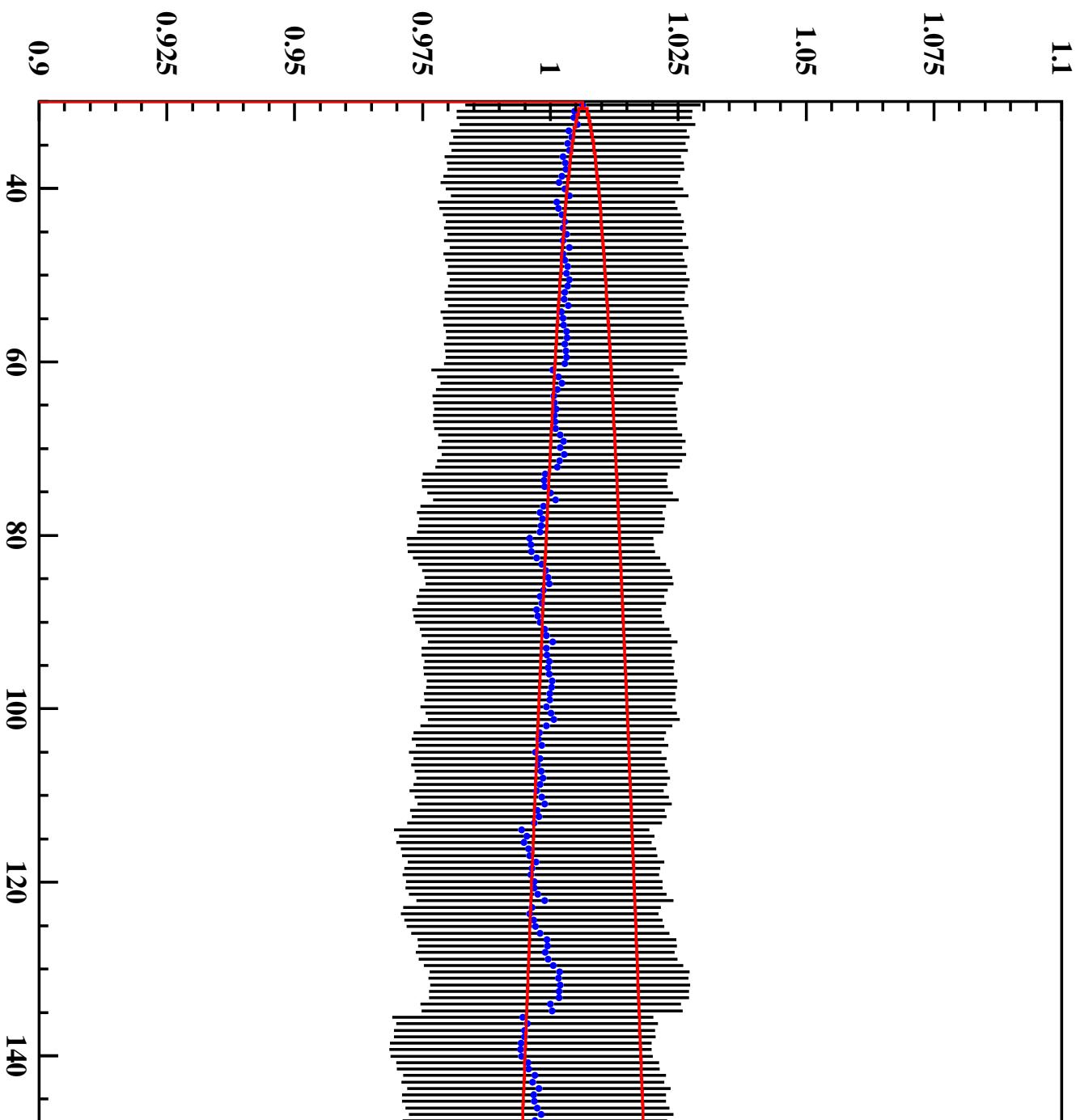
Detector Gain Stability

- average positron energy vs. time
Affected by background levels, rates, PMT gate-on time (more severe near injection point)
Stable $\approx 0.2\%$ over 10 muon lifetimes.
- $\sigma_{\omega_a}(\text{gain}) = 0.13 \text{ ppm (1999), } 0.12 \text{ ppm (2000), } 0.12 \text{ ppm (2001)}$

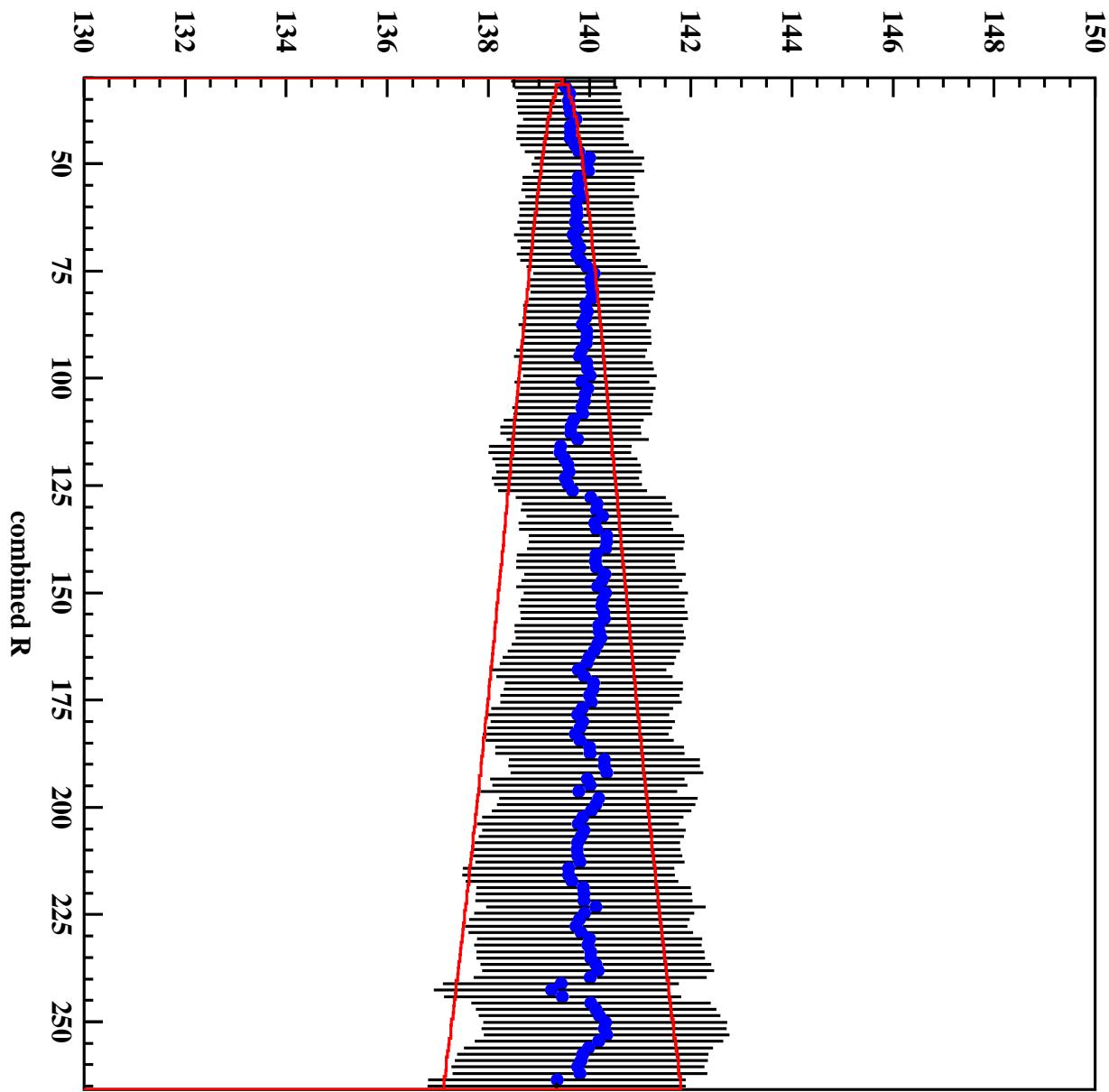
Future improvements

- Improved monitoring of gains- laser/LED
- Instrumentation of all detector channels
- Reduction of the 'flash' associated with particle injection
 - PMT can be gated on sooner, gain settles sooner
 - reduced background: calibration fits more reliable





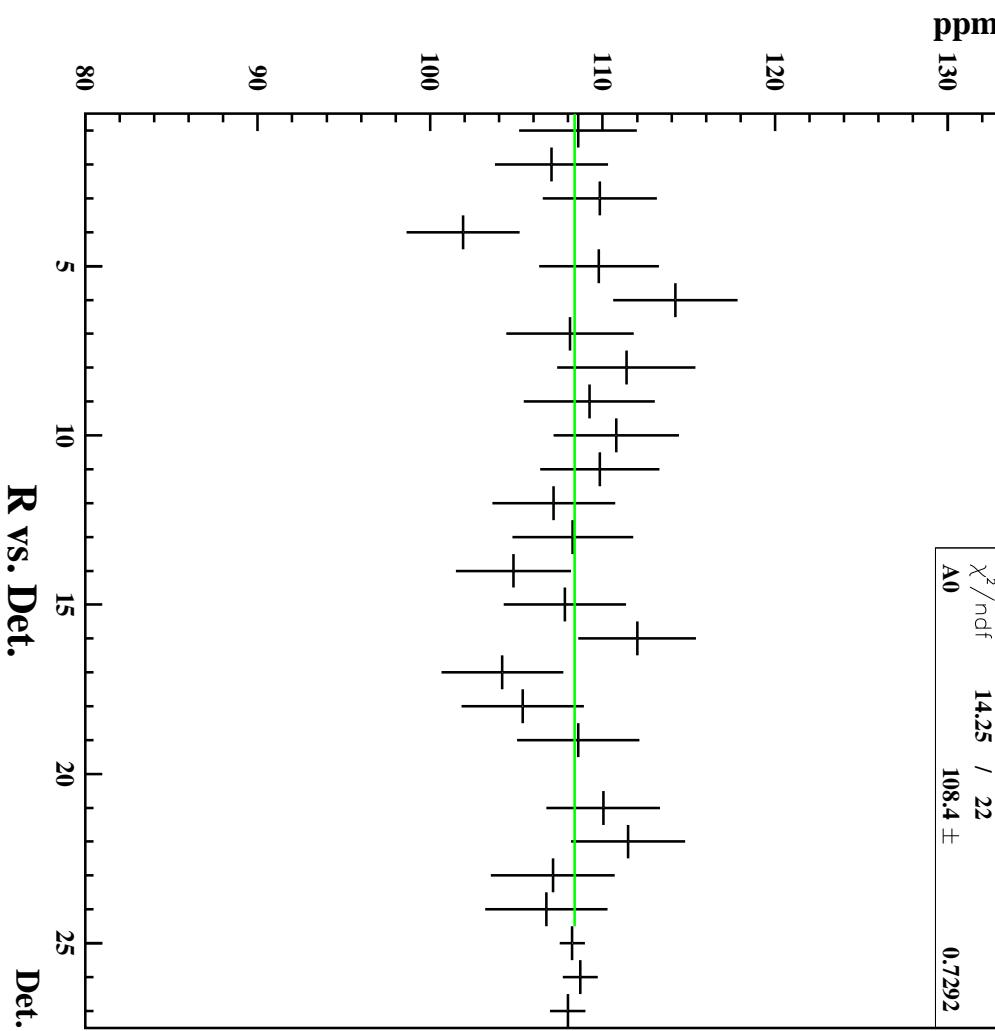
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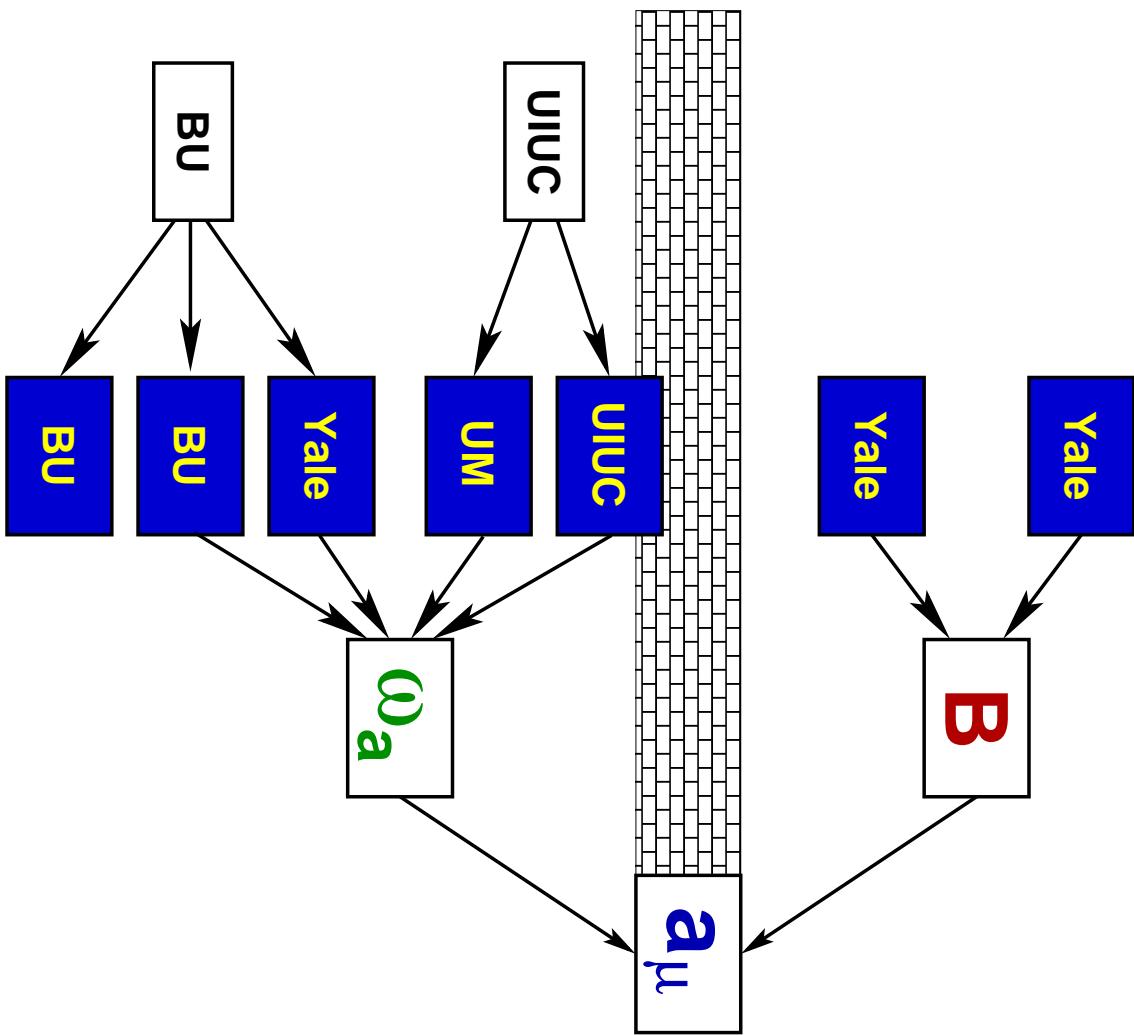
R vs. Detector, 9 par. ratio fit

All Data

	χ^2/ndf	/	A_0	\pm	0.7292
	14.25	/ 22	$108.4 \pm$		



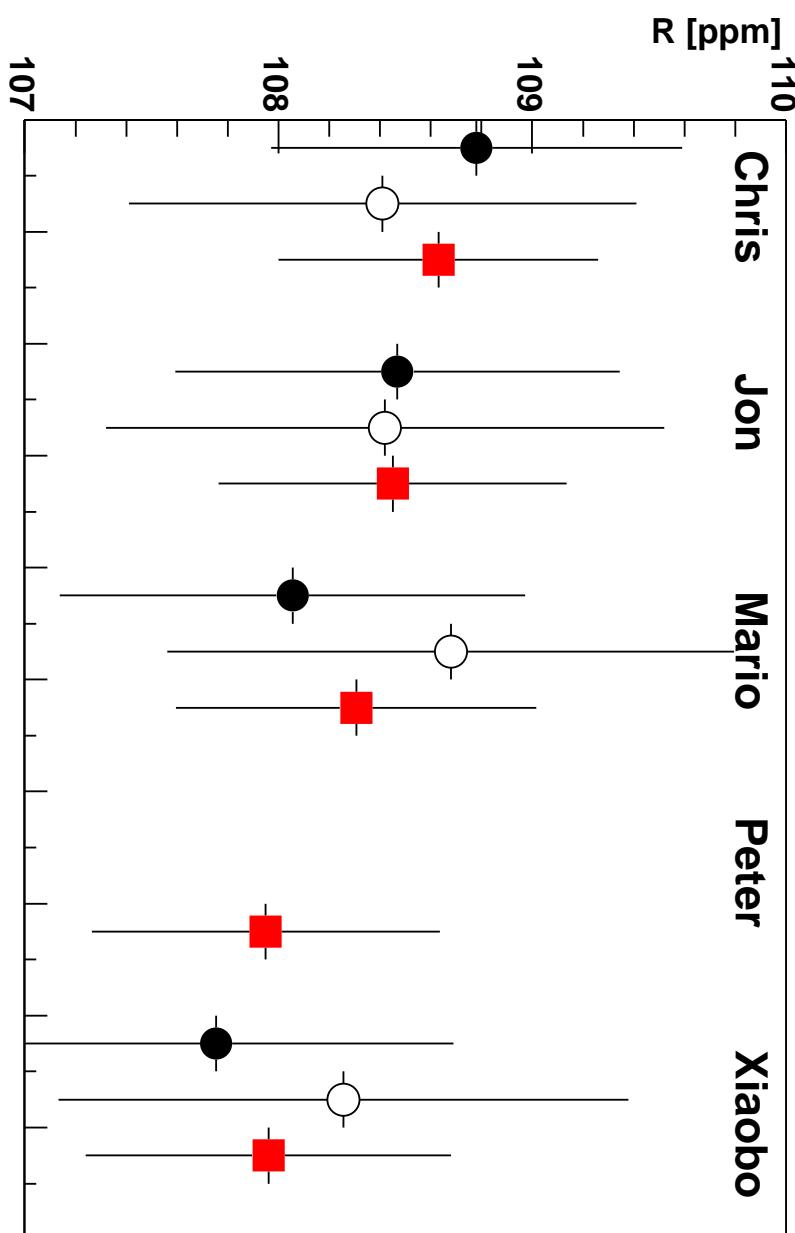
Analysis Strategy (2001 Data Set)

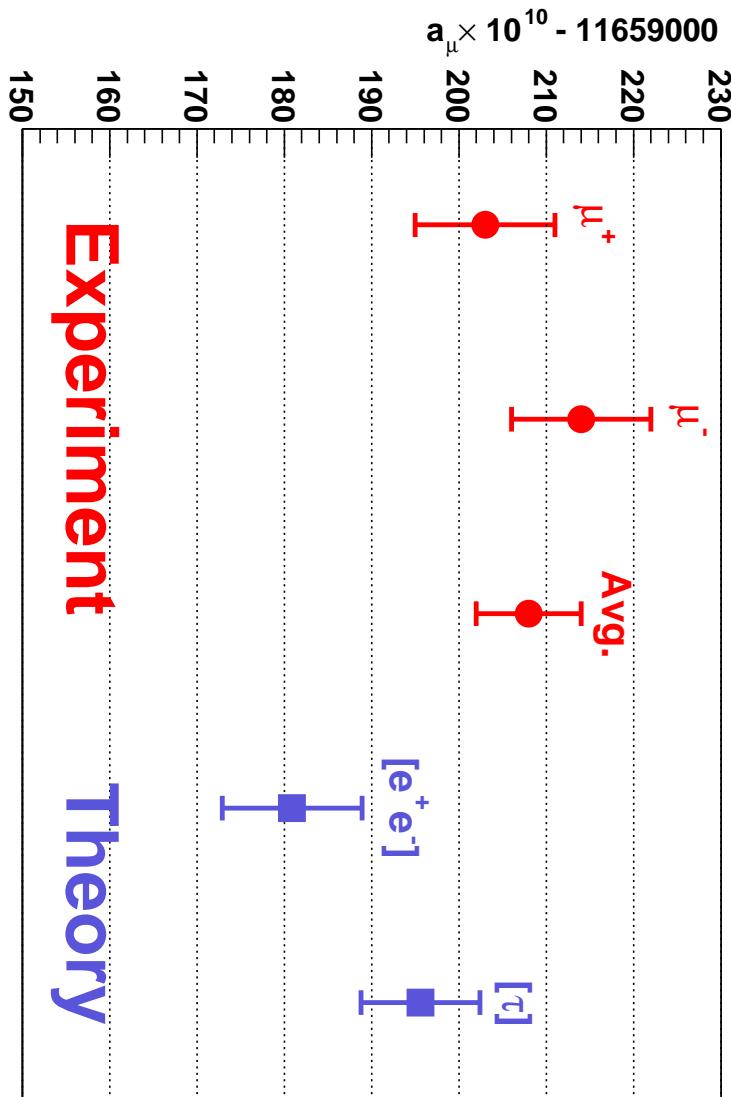


$$a_\mu = \frac{\omega_a}{\omega_p} / \left(\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p} \right)$$
$$\frac{\mu_\mu}{\mu_p} = 3.183\ 345\ 39(10)$$

Results of Independent Analyses, 2001 Data Set

$$\omega_a = \omega_0(1 - R)$$





Experiment Theory

$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.4 \text{ s.d.}$$

$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}$$

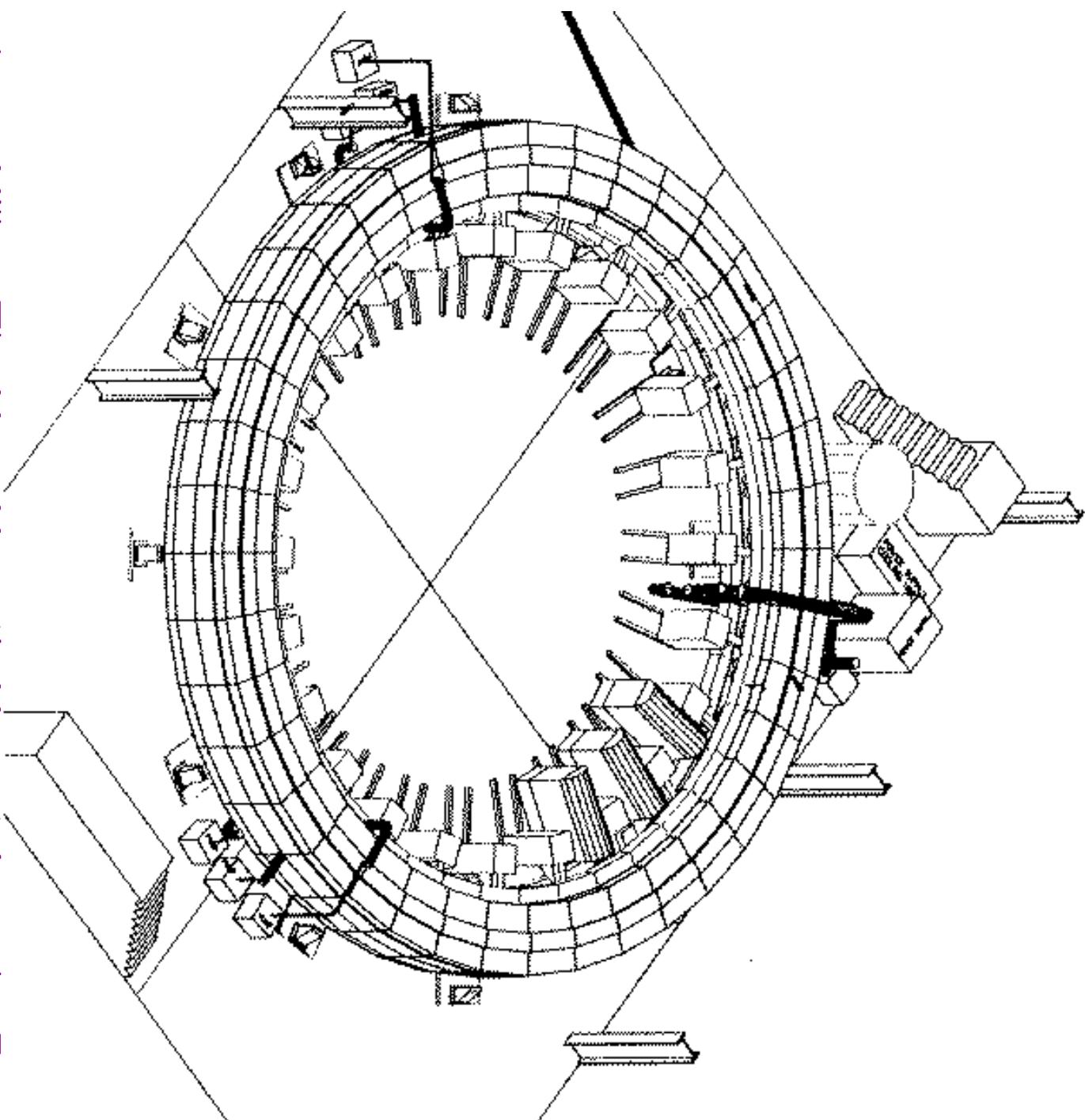
Conclusions

- a_μ data sets are consistent; a_μ^- (*expt*) agrees with a_μ^+ (*expt*)
- Experimentally, $\frac{\sigma_{a_\mu}}{a_\mu} = 0.5$ ppm is statistics limited and approaches our original goal of 0.35 ppm
- Combined $a_\mu \pm$ differs 2.4 s.d. (e^+e^-) or 0.9 s.d. (τ) from Davier and Marciano compiled theory value
- a_μ is expected to be sensitive to the presence of new particles beyond the standard model, especially supersymmetry with large $\tan(\beta)$
 - discovery potential if there is disagreement with SM
 - constraints on new models if there is agreement with SM
 - if LHC sees supersymmetric particle, then a_μ will give $\tan\beta$
- Many aspects of a_μ (*theory*) continue to be heavily scrutinized.
- A factor of two improvement in errors of both expt. and theory is highly desirable as a test of the SM, and is quite feasible.

Outlook

- New R data coming: VEPP upgrade to 2 GeV, radiative return data from DAPHNE, SLAC, Cornell...
 - e^+e^- vs. τ discrepancy, light-on-light calculations, continue to get a lot of attention from theorists
 - A proposal is being prepared for another data run, at x3 intensity, would enable a x2 reduction in uncertainty and a more definitive comparison with theory, at relatively modest cost.
- Please let us know if you are interested in joining the effort!
- Same type of new physics may lead to non-zero muon EDM: efforts under way to develop experiments to measure deuteron and muon EDM using the storage ring technique

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Determination of Average B-field (ω_p) over Muon Ensemble

Goal: Get the average precession frequency of the NMR protons in the same average B-field seen by stored muons.

Mapping of B-field

- Complete B-Field map of storage region (in vacuum!) every 3-4 days
- Beam trolley with 17 NMR probes, calibrated to standard probe to 0.09 ppm
- Continuous monitor of B-field with ≈ 150 fixed probes
- Two largely independent analyses of the B-field data, agree well

5-parameter function

$$N(t) = N_0 e^{-\lambda t} [1 + A \sin(\omega_a t + \phi)]$$

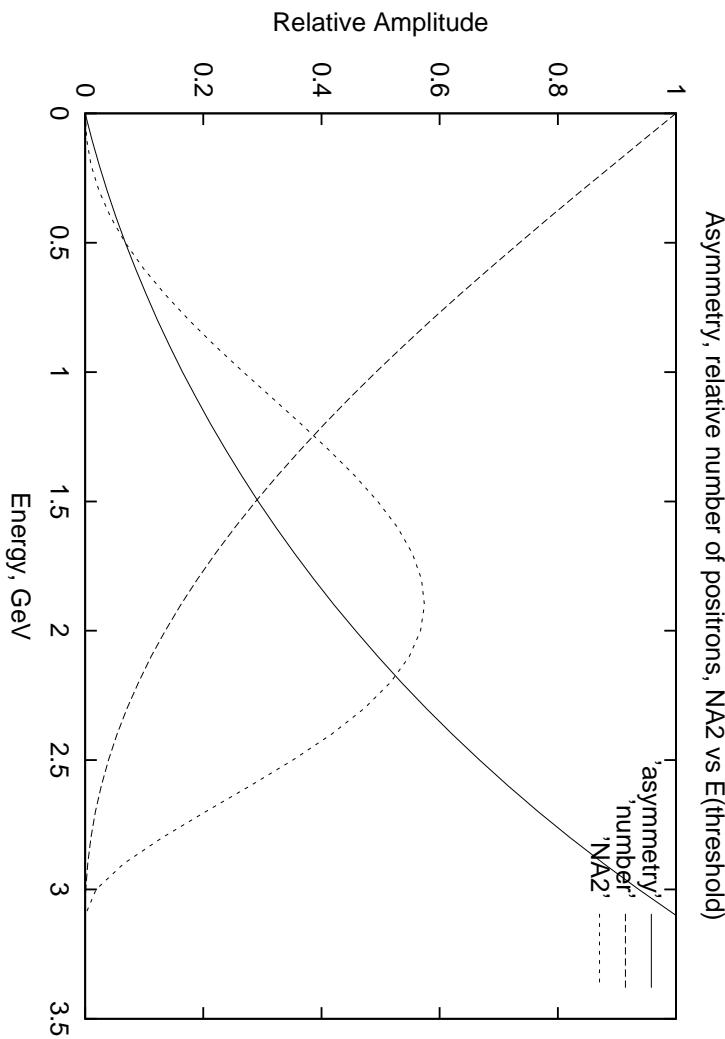
Small distortions important for high statistics sample.

- Positron pulses overlapping in time (pile-up)
- Coherent betatron oscillations
- Muon losses
- Detector gain stability

Determination of ω_a

Time distribution of positrons:
 $N(t) = N_0 e^{-\lambda t} [1 + A \sin(\omega_a t + \phi)]$

Statistical Error: $\frac{\delta \omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a \gamma \tau_\mu A \sqrt{N_e}}$



Dipole moments: Definitions

Magnetic: $\vec{\mu}_s = g_s \left(\frac{e}{2m}\right) \vec{s}$

Electric: $\vec{d}_s = \eta \left(\frac{e}{2mc}\right) \vec{s}$ (Violates T, P Symmetries)

For spin $\frac{1}{2}$

$$\mu = (1 + a) \frac{e\hbar}{2m} \quad \text{where } a = \left(\frac{g-2}{2}\right)$$

$$d = \eta \frac{e\hbar}{4mc}$$

$$\mu_e = 1.001 \ 159 \ 652 \ 193 \ \frac{e\hbar}{2m_e} \quad d_e = 6.9 \pm 7.4 \times 10^{-28} \ \text{e.cm}$$

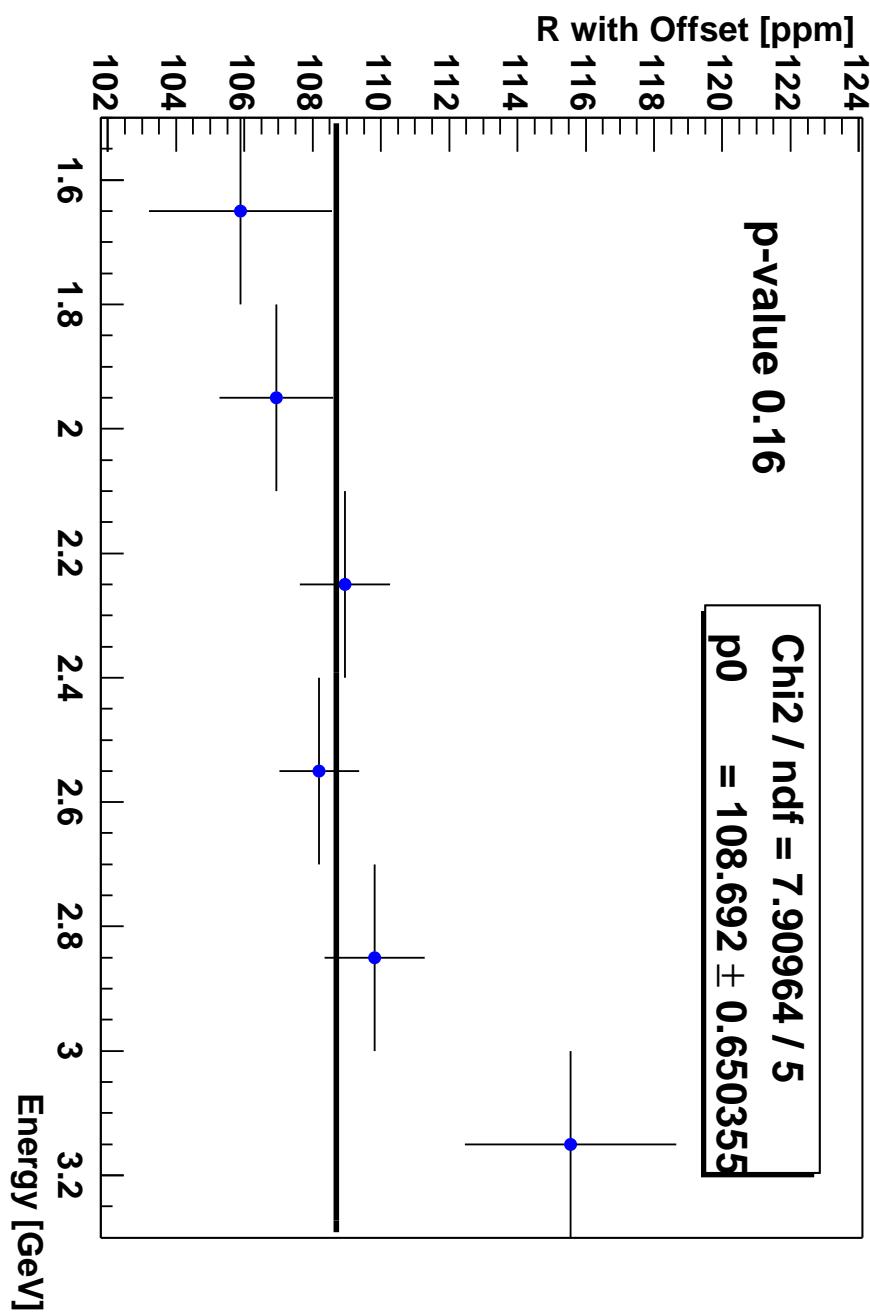
$$\mu_\mu = 1.001 \ 165 \ 165 \ 923 \ \frac{e\hbar}{2m_e} \quad d_\mu = 3.7 \pm 4.4 \times 10^{-19} \ \text{e.cm}$$

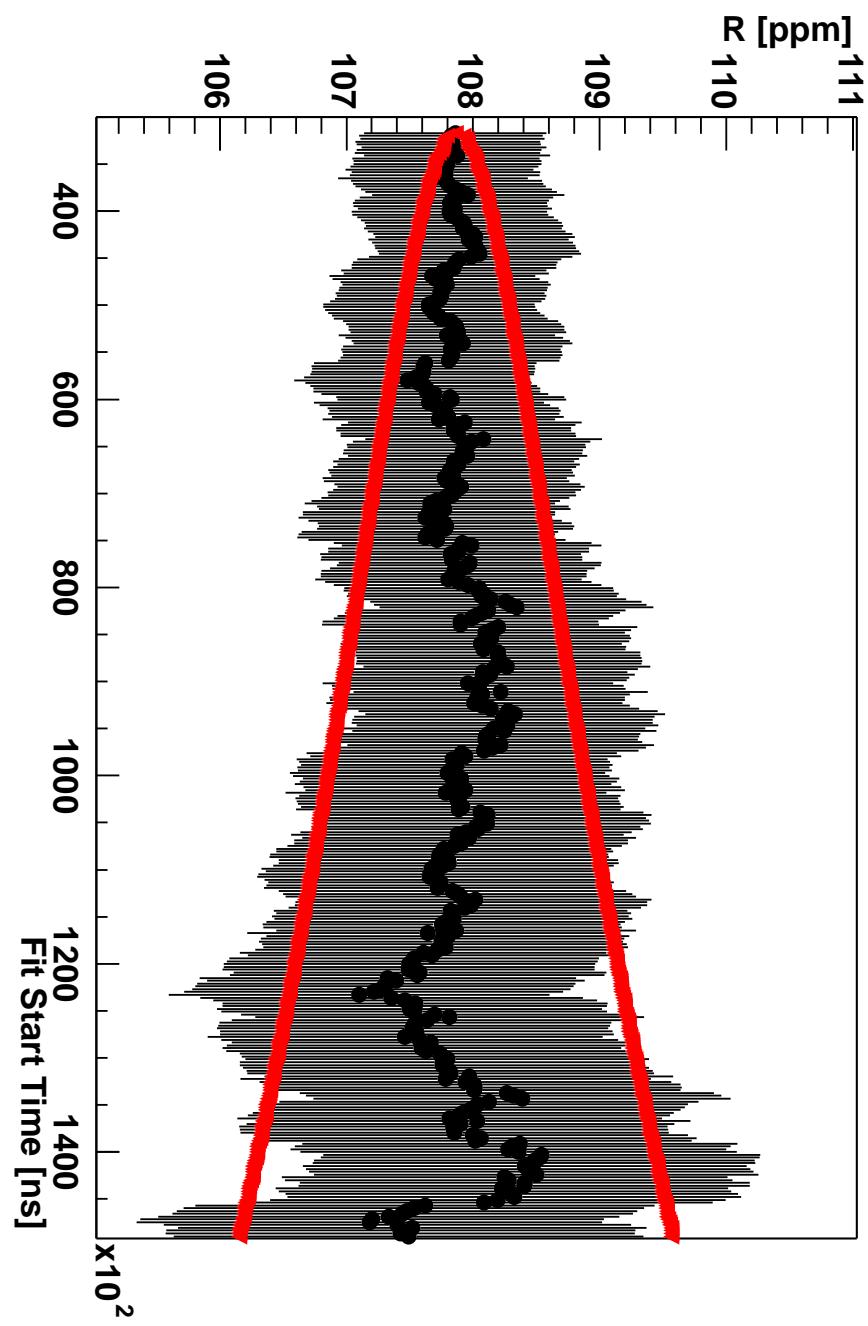
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Future RUN: Improvements in Average B-field

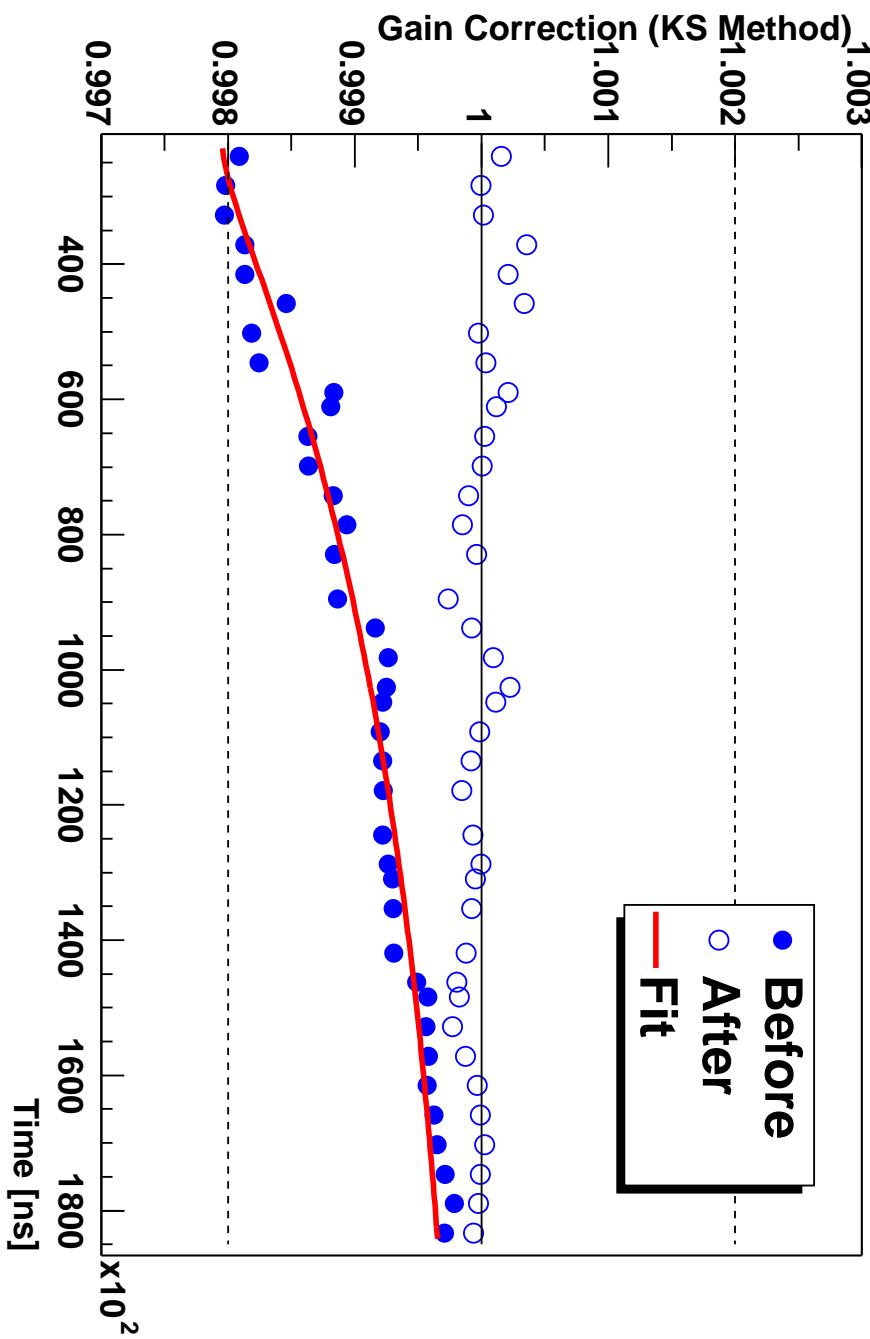
GOAL: Improve $\frac{\delta\omega_p}{\omega_p} = 0.17 \text{ ppm}$ to 0.10 ppm

- improve surface coil supply stability
- repair probes
- increase number of probes
- improve room thermal stability
- calibrate trolley in an external homogeneous field
- improve field homogeneity

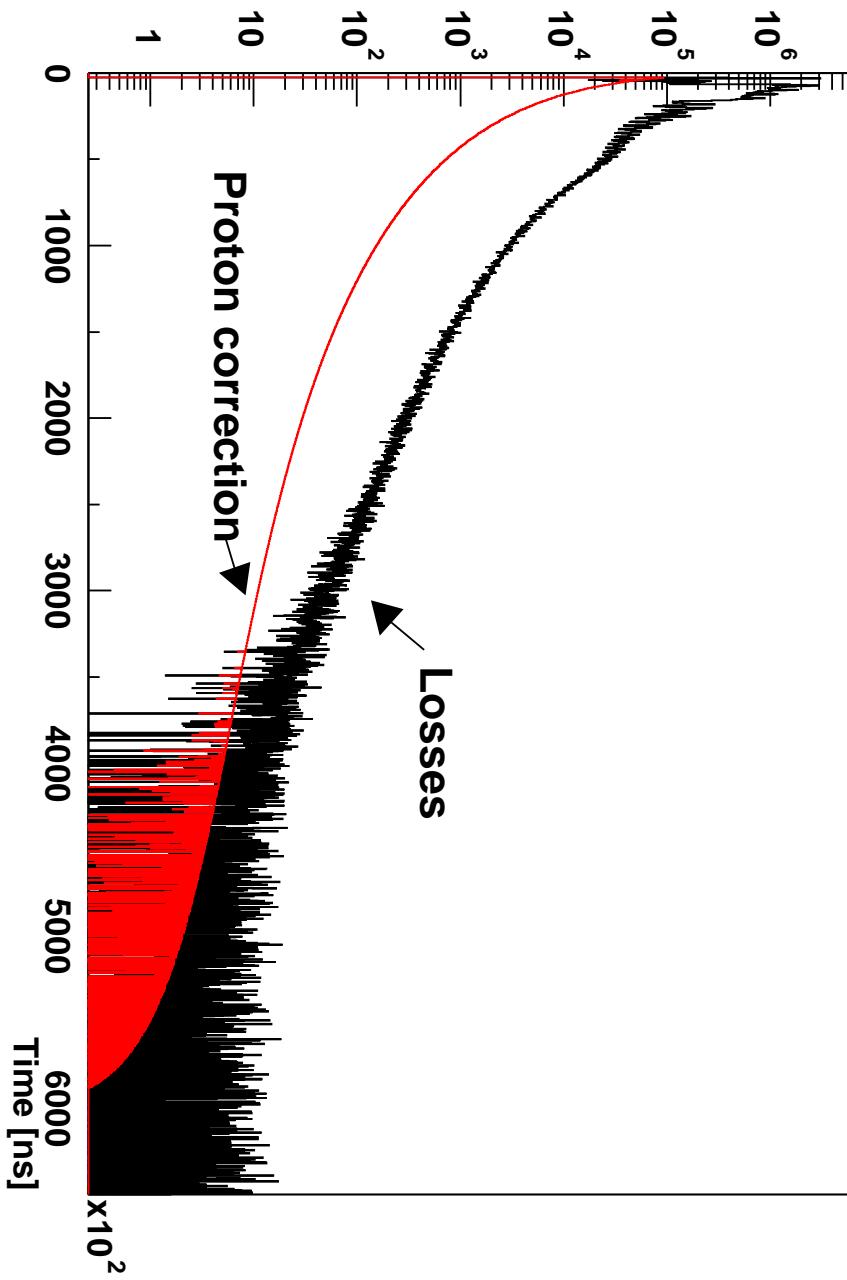


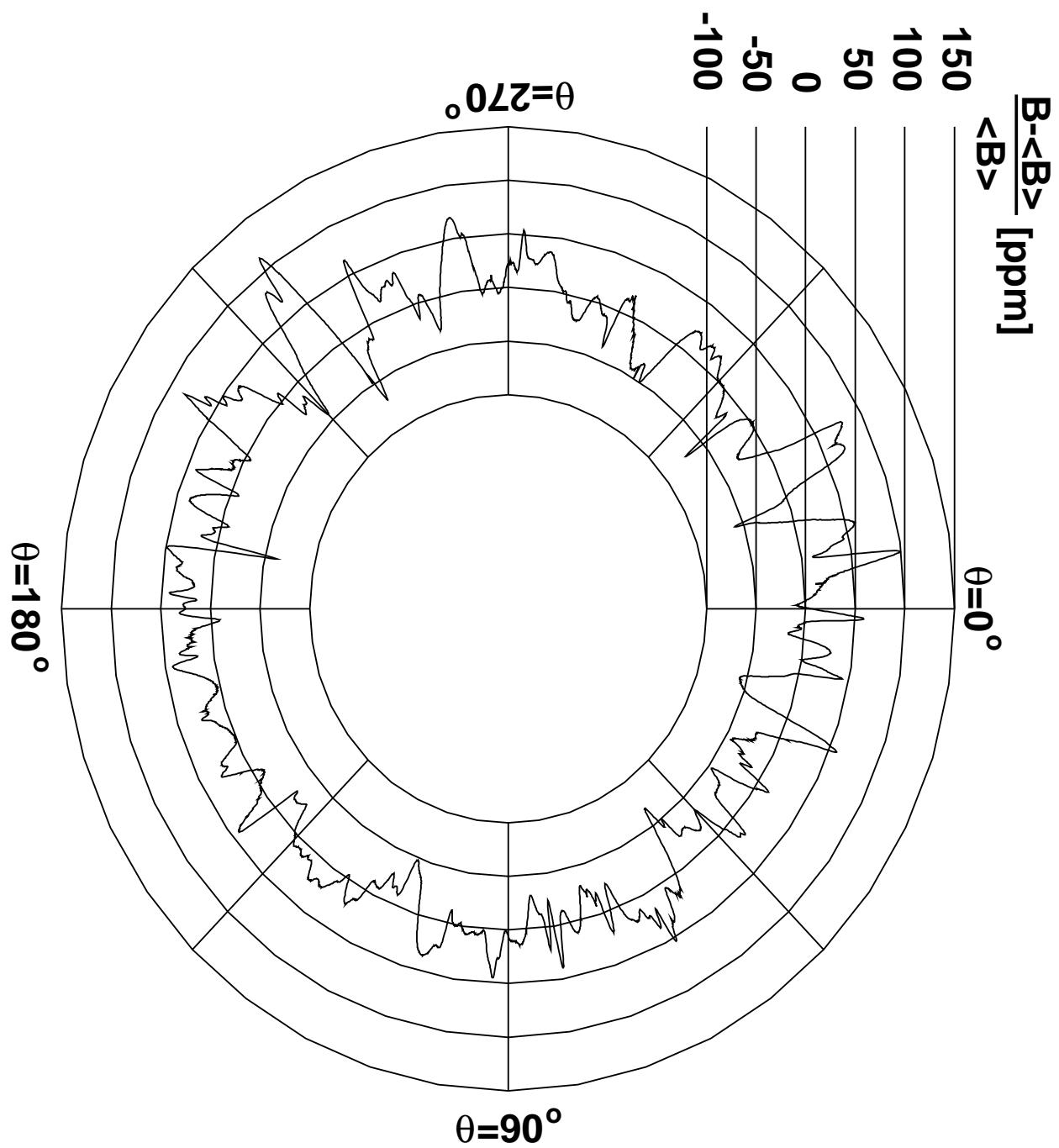


Station 21



Relative Number of Muon Losses vs. Time





Standard Model Value for a_μ [1]

$$\begin{aligned} a_\mu(QED) &= 116\ 584\ 72.07(0.11) \times 10^{-10} \\ a_\mu(HAD; 1) &= 694.4(7.2) \times 10^{-10} \quad (e^+e^-) \\ a_\mu(HAD; 1) &= 711.0(5.8) \times 10^{-10} \quad (\tau) \\ a_\mu(HAD; > 1) &= -9.8(0.1) \times 10^{-10} \text{ (Except LBL)} \\ a_\mu(HAD; LBL) &= 12.0(3.5) \times 10^{-10} \\ a_\mu(EW) &= 15.4(.2) \times 10^{-10} \\ &\rightarrow 116\ 591\ 84.1(8.0) \times 10^{-10} \text{ (0.7 ppm)} \quad e^+e^- \\ &\rightarrow 116\ 592\ 00.4(6.8) \times 10^{-10} \text{ (0.6 ppm)} \quad \tau \end{aligned}$$

[1] M. Davier, W. Marciano, Ann. Rev Nucl. and Part. Phys. (2004)

FNAL James Miller - The Muon Magnetic Moment Anomaly: Experiment

